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**STRATOSPHERIC TEMPERATURE PATTERNS
BASED ON
RADIOMETRIC MEASUREMENTS
FROM
THE TIROS VII SATELLITE**

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**STRATOSPHERIC TEMPERATURE PATTERNS BASED
ON RADIOMETRIC MEASUREMENTS FROM THE
TIROS VII SATELLITE**

by

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ABSTRACT

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The TIROS VII meteorological satellite carried a sensor to map the emitted terrestrial radiation in the 15 micron carbon dioxide band. The spectral response of the sensor ranged from 14.8 to 15.5 microns. The radiation observed by the satellite is a function of the temperatures of the atmosphere varying along the optical path. Atmospheric layers at various altitudes contribute to the observed radiation in varying amounts. More than 96 percent of this contribution stems from altitudes above 10 km and more than 60 percent from a layer ranging in altitude from 18 to 35 km; thus, the radiation measurements were interpreted in terms of average temperatures of a major portion of the stratosphere.

Temperature patterns were analyzed from June 1963 to March 1964. The measurements demonstrate on a global scale, the varying patterns of stratospheric temperatures and circulation. Smooth temperature gradients were found to coincide closely with latitudinal circles on both summer hemispheres. Temperatures increased at high latitudes toward the summer pole (250°K) and rapidly decreased toward the winter pole (200°K).

A fairly uniform region with temperatures generally around 230°K extended between 25° latitude of the summer hemisphere and 40° latitude of the winter hemisphere during solstices. During both equinoxes, the large latitudinal temperature gradients at high latitudes disappeared and differences of about $10\text{--}15^{\circ}\text{K}$ existed with latitudes as well as with longitude. Winter temperature patterns in both hemispheres exhibit strong temperature gradients between the pole and 40° , but a completely uniform pattern never existed in either winter hemisphere. A warm area over the Indian Ocean, though initially small, seemed to play a similar role in the southern winter as the Aleutian warm center during the northern winter. The morphology of a stratospheric warming which occurred over southwestern Asia and penetrated to Europe immediately after the tropical belt had cooled by about 10°K was observed.

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I. INTRODUCTION

A radiometer aboard the TIROS VII satellite measured infrared radiation emitted mainly by carbon dioxide in the earth's atmosphere at wavelengths ranging from 14.8 to 15.5 microns. The instrument in this measurement was very similar to the 5 channel radiometers flown on previous TIROS satellites and described by Bandeen, et.al.(Reference 1), except that one of the optical channels was modified to have a spectral response as shown in Figure 1a. The initial objective of radiation measurements in this region of the spectrum was to study the characteristics of the earth's horizon as described by Hanel, et. al.(Reference 2) and later reported by Bandeen, et. al.(Reference 3). Now, with continuous observations over a period of more than six months, covering daily the global zone from 65° N to 35° S, it is possible to use the radiation measurements to describe a number of interesting features of the atmosphere. It will be shown that most of the radiation reaching the satellite in this spectral region is emitted within a defined altitude interval in the stratosphere whose average temperature can be derived from the observed radiation intensities. Quasi-global maps of these average temperatures for different seasons not only reflect the expected variations in the mean stratospheric temperatures, but also reveal the development and behavior of major synoptic systems in that region of the atmosphere. A complete description of the 5 channel radiation experiment on TIROS VII as well as a critique and summary of all data resulting from this experiment will be contained in the TIROS VII Radiation Data Catalog and Users' Manual (Reference 4).

II. RELATION BETWEEN RADIATION AND STRATOSPHERIC TEMPERATURES

The spectral response of the instrument was chosen to coincide as closely as possible with the 15 micron absorption band of carbon dioxide. The radiance N from the earth and

atmosphere measured by the radiometer whose spectral response function $\phi(\lambda)$ is shown in Figure 1a can be expressed as:

$$\bar{N} = \frac{1}{\pi} \int_0^{\infty} \int_{\lambda_1}^{\lambda_2} \phi(\lambda) B(\lambda, T) \frac{\partial \tau}{\partial s} (\rho, p, T, \lambda) d\lambda ds \quad (1)$$

where

ρ = carbon dioxide density

B = Planck function

s = distance along radiation path

λ_1 and λ_2 = wavelengths between which $\phi \neq 0$

p = atmospheric pressure

T = atmospheric temperature

τ = atmospheric beam transmissivity

It is reasonable to assume that a constant ratio $r = 0.000471$ exists between the densities ρ for carbon dioxide and ρ_{air} for air: $\rho = r \rho_{\text{air}}$. Furthermore, a number of typical distributions for temperature with height h for surface pressures of 1013.25 mb were chosen so that ρ_{air}, p and T could be expressed as functions of h where ρ_{air} and p were computed as a function of h from T by the hydrostatic equation. A relationship between s and h , $s = s(h)$, was established through the choice of several angles at which the satellite at approximately 635 km viewed the earth. The integration of (1) over λ was then performed for seven nadir angles, $0^\circ, 29^\circ, 40^\circ, 47^\circ, 52^\circ, 55^\circ$, and 58° . The function $\tau(\lambda, h)$ was determined using, in principle, the method described by Hanel, et. al. (Reference 2). That method is based on the general treatment by Elsasser (Reference 5) of the absorption within the 15 micron CO_2 band. Thus,

$$\int_{\lambda_1}^{\lambda_2} \phi(\lambda) B(h, \lambda) \frac{\partial \tau}{\partial s}(h, \lambda) \frac{\partial s}{\partial h} d\lambda = \gamma(h). \quad (2)$$

$$\text{Hence, } \bar{N} = \frac{1}{\pi} \int_0^{\infty} \Psi(h) \, dh. \quad (3)$$

\bar{N} was then computed for each of the assumed temperature profiles and for each nadir angle from (3). The assumed temperature distributions with height and the resulting distribution functions $\Psi(h)$ are shown in Figures 2a through 2c. In accordance with previous practices of reporting TIROS radiation measurements (References 4, 6-8) \bar{N} may be expressed by the temperature T_{BB} of a blackbody whose radiant emittance W is given by:

$$W = \int_{\lambda_1}^{\lambda_2} \phi(\lambda) E(T_{BB}, \lambda) \, d\lambda = \pi \bar{N} \quad (4)$$

Indeed, since the radiometers were calibrated using such blackbodies at various temperatures, the measurement of T_{BB} may be considered as the primary quantity while \bar{N} requires a derivation by means of equation (4). The values of T_{BB} corresponding to the temperature profiles of Figure 2a are summarized in Table I.

TABLE I: COMPUTED MEAN TEMPERATURES (T_{BB}) EXPECTED TO BE OBSERVED BY 15 MICRON RADIOMETER FOR TEMPERATURE PROFILES SHOWN IN FIGURES 2a AT NADIR ANGLES OF 0° AND 58° .

Nadir Angle	Tropical	High Lat. Summer	High Lat. Winter Cold	High Lat. Winter Warm
0°	227° K	238	213	229
58°	231	240	214	231

The radiation measurement expressed by T_{BB} thus represents a mean temperature of the atmosphere in which the vertical temperature distribution is open to choice and where the temperature at each altitude must be given a different weight

regarding its contribution to the measured mean. The weighting function is given by $\Psi(h)$, and although $\Psi(h)$ depends to a certain degree on the assumed vertical temperature profile, it may be seen that for most realistic temperature profiles at a nadir angle $\eta = 0$ (Figure 2b), temperatures between 20 and 25 km are weighed most heavily with about 65 percent of the weight being concentrated in the region from 15 to 35 km and more than 96 percent of the weight lying at altitudes above 10 km. It may also be seen from Figure 2c that the maximum weight shifts to somewhat higher altitudes for a nadir angle of 58° . But, since this shift amounts to less than 5 km from $\eta = 0$ to $\eta = 58^\circ$, it is not possible to make a precise quantitative determination of the variation of temperature with altitude from measurements of T_{BB} at various nadir angles. However, it will be shown in the section below that from such measurements one may infer qualitatively whether the temperature is increasing, decreasing, or constant with height over the altitude range where the functions reach their maxima. Furthermore, with a prudent and realistic choice of assumed vertical temperature profiles, such as shown in Figures 2a, one can easily determine from the T_{BB} measurements which one of these profiles represents the best fit qualitatively to actual conditions at a certain location on the globe and; more important, one may determine from continuous observations how the choices of such "best fits" vary with time. Thus, the maps of T_{BB} measurements plotted for the "quasi-global" (65° N to 65° S) zone for different times of the year, presented in Figures 3-12, enable the synoptic analysis of phenomena related to the temperature structure in the stratosphere between about 15 and 35 km. The occurrence of such events as explosive warmings, the establishment of the Aleutian anticyclone in winter, the onset of the seasonal circulation reversals and similar events may be categorized as such phenomena. Although the TIROS VII radiometer

views the entire global zone from 65° N to 6° S during the course of 12 hours, data from only about 60 percent of the orbits during any one day can be acquired because only stations within the United States are capable of receiving the data which are stored aboard the satellite for no longer than one orbital period. This causes two significant gaps in the data displayed in the maps, Figures 3-12. One such gap exists at 90° W just off the west coast of South America, the other is at 90° E over the central Soviet Union.

As will be stated in the TIROS VII Radiation Data Catalog and Users' Manual (Reference 4) the precision of each individual measurement is probably not much better than $\pm 2^{\circ}\text{K}$. However, one may assume that the physical properties of the stratosphere remain generally constant for several days and are uniform over distances of less than 500 km. Since the field of view of the radiometer is about 3 degrees, covering an area of about 50×50 km on the surface of the earth for small nadir angles, and since in general measurements for the entire quasi-globe are obtained at least once every 24 hours, up to about 1000 measurements may result within one week within an area of about 500×500 km. Therefore, a precision of better than 1°K can be estimated for the temperature values shown in the maps, Figures 3-9 and 11-12, which were obtained by averaging measurements within each grid element (ranging from 5° latitude \times 5° longitude at the equator to 2.5° latitude \times 5° longitude at 60° latitude) over the period of one week.

Although the precision of the temperature measurement is greatly enhanced by reducing the random error in the averaging process, there are a number of systematic errors which must be considered. It has been attempted to reduce these errors by applying the appropriate corrections, but uncertainties still remain, causing the overall accuracy to be considerably poorer than the fraction of 1°K stated for the precision. Aside from correcting for an instrumental degradation which will be discussed later, a correction was applied to the data for an as

yet unexplained deviation from the original preflight calibration. The radiometer, which alternately views the earth through one of two viewing ports showed that a consistently lower response on one of these viewing ports with respect to the other were apparently causing half of the measured temperatures to be too low and half to be too high. According to the preflight calibration, there should be no such difference. For lack of a better correction procedure, the difference between the temperatures measured through the two viewing ports over the same area at the same time were determined for all cases shown in the maps in Figures 3 through 12. Temperatures for the lower side were then corrected upward by half this difference, while those for the higher side were corrected downward by the same amount. Total differences were generally 5 to 8°K, so that the corrections were in the order of 2.5 to 4°K.

The maps were prepared from the magnetic tapes (FMRT's) containing all the TIROS VII radiation data (Reference 4) by an IBM 7094 computer and contour lines were drawn manually. This mapping procedure was the same as the one used in previously published similar maps (Reference 9).

III. ANALYSIS OF STRATOSPHERIC TEMPERATURES, JUNE 1963 TO MARCH 1964

A. Solstice June 1963

A typical temperature pattern at the start of the northern hemisphere summer and southern hemisphere winter for the quasi-globe is shown in Figure 3a. Stratospheric mean temperatures averaged over nadir angles between 0° and 40° and averaged over the week from 19 June to 25 June, the first week of TIROS VII, range from 240°K near 60° N to 215° near 60° S. The generally zonal structure of the temperature pattern, with isotherms running practically parallel with latitude circles, confirms the established knowledge of the physics of the lower

stratosphere; namely, the existence of a very strong cyclonic circulation system around a low pressure core centered near the winter pole. This low pressure is caused by the intense cooling of the stratosphere over the winter pole. Conversely, anti-cyclonic circulation prevails over the summer pole where solar heating causes a warm stratosphere resulting in a high pressure system. The predominantly zonal isotherms at high northern latitudes (summer) suggest that solar heating is primarily responsible for this pattern. At high southern latitudes (winter) however, there are slight but apparently significant disturbances in this zonal pattern. Isotherms over the South Pacific between 30° S and 60° S deviate from a perfect zonal course; they show a definite slope from the southwest to the northeast in that area. Temperatures increase rapidly from the winter pole toward the equator causing very steep temperature gradients with latitude in the winter hemisphere. A temperature of about 230°K is reached near 20° S. From there to the summer pole, the temperature increases gradually, and the gradients are not as steep as over the winter hemisphere. This is expected and it demonstrates clearly that the winter cyclone is considerably stronger than the summer anticyclone. The measured mean temperatures of 215°K near 60° S and of 240°K near 60° N agree reasonably well with the computed values of 213° and 238°K respectively (Table I) for the temperature profiles for high latitude cold winter and summer shown in Figure 2a. The measured temperatures of 230°K within the belt 40° S to 25° N are 3°K higher than those computed (Table I) for the tropical temperature profile shown in Figure 2a. This disagreement with the computation seems to be consistent with the cases at 60° N and 60° S where the measured temperatures were 2°K too high. The reason for this consistent discrepancy could be due to a number of assumptions contained in the radiative transfer calculations which may have resulted in the computed values of T_{BB} being several degrees too low.

A coarse picture of the temperature gradient with altitude can be obtained by comparing Figures 3a and 3b. In Figure 3a, temperatures measured at nadir angles between 52 and 58 degrees were plotted. The weighting functions in Figures 2b and 2c show that all measurements shown in Figure 3b reflect temperatures at altitudes approximately 3-4 km higher than the temperatures shown in Figure 3a. Thus, by comparing Figures 3a and 3b, one may distinguish three categories in the temperature profiles:

1. Increasing temperatures with altitude between 15 and 35 km where the measured temperature differences are positive.
2. Decreasing temperatures with altitude between 15 and 35 km where the measured temperature differences are negative.
3. Isothermal regions between 15 and 35 km if the temperature differences are close to zero.

It can be seen that differences of about $+2^{\circ}\text{K}$ occur in the tropics where strongly positive temperature gradients with altitude prevail. This difference agrees reasonably well with the values calculated for a tropical profile (Table I). Over the higher northern latitudes (summer) moderately increasing temperatures with altitude and over high southern latitudes (winter) isothermal temperatures are suggested. This is in fair agreement with the calculations (Table I).

B. Seasonal Reversal, September - October 1963

As the solar illumination gradually becomes symmetrical with respect to northern and southern hemispheres during September, 1963, temperature patterns at high latitudes markedly reflect the resulting change in solar heat input. In some areas, this change takes place rapidly while other regions undergo a much slower transition. During the first two months following the solstice, there were practically no temperature gradients along any given latitude circle in the northern hemisphere; but strong longitudinal temperature patterns begin to develop now during the transitional season, especially after the September equinox. During July and

August, the temperature patterns remain essentially the same as those during 19-25 June, shown in Figure 3a. There is one important change, however, which exhibits the same characteristics as similar changes observed on measurements in other spectral regions in previous TIROS satellites (References 7 and 3). All measured temperatures over the entire world seem to decline during the first three weeks of observation. It is extremely probable that a gradual degradation in the response of the radiometer is the cause for this decline. By mid-July 1963, the magnitude of this sensitivity decrease is about 7°K . After that, the degradation seems to have leveled off and continued at a much lesser rate. An approximate time history of this instrumental degradation based on the preliminary information available at this time is given in Figure 1b. A more complete version will be given in the TIROS VII Radiation Data Catalog and Users' Manual (Reference 4). An appropriate correction based on Figure 1b should, therefore, be added to all temperature measurements quoted thereafter and shown in the maps, Figure 4 to 12. Although this degradation leaves some uncertainties in the exact absolute magnitudes of the temperature measurements, it does not appreciably affect the ability to assign the appropriate temperature profile (Figure 2a) to a measurement at a given location or the implications drawn from the distribution of relative temperature patterns.

The first indication of any significant change in the post solstice temperature pattern occurs during the week 28 August to 3 September: the temperatures at high northern latitudes decrease by about 5°K to a temperature of about 228°K ($+7^{\circ}$ correction) at 60°N . At northern mid-latitudes ($20^{\circ} - 50^{\circ}\text{N}$) there is also a slight temperature decrease from the summer (19-25 June) conditions. However, here this decrease does not take place uniformly at all longitudes. There are pocket-like

regions where warmer temperatures seem to persist longer than over other regions causing some inhomogeneities in contrast to the uniform zonal pattern observed in June. Going southward, temperatures in general decrease very gradually from about $228 + 7^{\circ}\text{K}$ at 60°N to about $223 + 7^{\circ}\text{K}$ at 40°S with the latter temperatures prevailing over most of the zone from about 25°N to 40°S . From there southward temperatures decrease rapidly with latitude. Thus, the remainder of the southern hemisphere remains essentially unchanged, still reflecting typical winter conditions ($205 + 7^{\circ}\text{K}$ at 60°S) except for a warm region of $225 + 7^{\circ}\text{K}$, which developed during later winter over the Indian Ocean between 40° to 50°S . The disturbance noted during June at these latitudes over the western South Pacific has grown throughout July and early August, and a warm region extends now over the entire Indian Ocean showing a definite longitudinal pattern. For example, temperatures over the southern Indian Ocean at 60°S are about $218^{\circ} + 7^{\circ}\text{K}$. At the same latitude over the Atlantic and central South Pacific, temperatures are $213 + 7^{\circ}\text{K}$ and $203 + 7^{\circ}\text{K}$ respectively.

During September, the European and West Asian portions of the northern hemisphere and parts of North America begin to cool off rapidly. There temperatures at 60°N have cooled to about $223 + 7^{\circ}\text{K}$ while over the northwest Atlantic and North Pacific somewhat warmer temperatures still prevail ($228 + 7^{\circ}\text{K}$) during the week of 11-18 September (Figure 4). At the same time, the breakdown of the winter over the southern hemisphere is gaining impetus. The same, even intensified longitudinal patterns as observed in August are apparent. Temperatures in the Indian Ocean warm area amount up to $234 + 7^{\circ}\text{K}$. This area has now spread out between the longitudes of 95° to 180°E along the 50° parallel, yet temperatures at this latitude over the South Atlantic and the eastern South Pacific still remain relatively cold ($220 + 7^{\circ}\text{K}$). Temperatures at low and mid-latitudes, in general, range around $225 + 7^{\circ}\text{K}$ (Figure 4).

The week following the equinox (25 September - 1 October) shows that the temperature gradients between the two hemispheres (Figure 5) have reached their minimum during this transition period. With the exception of the very warm region at 50-55° S over the Indian Ocean reaching maximum temperatures of $236 + 7^{\circ}\text{K}$ at 70° E temperatures over the entire quasi-globe are nearly constant at $225 + 7^{\circ}\text{K}$. It is significant to note that at most longitudes the temperature gradient along a given latitude belt can now be much greater than gradients between 60° N and 60° S: temperatures along 50° S vary from $236 + 7^{\circ}\text{K}$ at 70° E to $223 + 7^{\circ}\text{K}$ near 170° W, while along the 180th meridian, for instance, temperatures at 60° S are about $222 + 7^{\circ}\text{K}$, at 60° N about $228 + 7^{\circ}\text{K}$ and at the equator about $223 + 7^{\circ}\text{K}$. This is a total variation of 6°K along the meridian compared to a variation of 13°K along the 50° S parallel (Figure 5). The phenomenon of very pronounced temperature differences between the Indian and Pacific Oceans at all latitudes between 40° S and 65° S persists during the entire transition period from winter to summer. The maximum temperature difference is about 15°K throughout this time, with the Indian Ocean area showing the warmest and the eastern South Pacific showing the coldest temperatures (Figure 5). This phenomenon first appears in large scale during the middle of August and lasts until about 20 October. During early and middle October, the eastern portion of the southern hemisphere (40° W to 120° E) is relatively warm ($230 + 7^{\circ}\text{K}$ at 60° S) with a warm center of $234 + 7^{\circ}\text{K}$ at 80° E, while the western portion remains relatively cold with the cold center at $220 + 7^{\circ}\text{K}$ at 170° E. During late October, the week of 23rd to 29th, the entire southern hemisphere finally achieves a typical summer temperature pattern with wide and uniform latitudinal temperature belts ranging from about $230 + 7^{\circ}\text{K}$ at 60° S to about $225 + 7^{\circ}\text{K}$ at 30° S. There is a uniform belt with temperatures of almost exactly $225 + 7^{\circ}\text{K}$ between 30° S and 30° N. Over the Atlantic, Europe and Western

Asia, temperatures drop rapidly from $225 + 7^{\circ}\text{K}$ at 30°N to $215 + 7^{\circ}\text{K}$ at 60°N , while over the Pacific they remain at $225 + 7^{\circ}\text{K}$ up to 60°N .

During the entire fall transition period the north Pacific area has not cooled off as rapidly as the rest of the northern hemisphere and in general remains warmer throughout much of the winter. During the course of October, this pattern intensified whereby temperatures in all northern regions except over the north Pacific and eastern Asia continue to decline. Finally, at the end of October, as stated above, the northern hemisphere shows a typical winter pattern with the same tight gradients with latitude as observed three months previously in the southern hemisphere. At 60°N , temperatures are uniformly cold ($215 + 7^{\circ}\text{K}$) over Eurasia, the North Atlantic and North America, but warm over Alaska and the Bering Sea ($225 + 7^{\circ}\text{K}$). The global picture does not change appreciably between the end of October and the week 20-26 November shown in Figure 6. Although the warm area ($224 + 7^{\circ}\text{K}$) over the North Pacific has somewhat diminished in size compared to the end of October, and it is now located over the Gulf of Alaska, the isotherms over that area still show a very definite departure from a zonal pattern and run northwest to southeast over North America and northeast to southwest over east Asia. While temperatures are still uniform with latitude over the Atlantic and Eurasian continent and range from $213 + 7^{\circ}\text{K}$ at 60°N to $225 + 7^{\circ}\text{K}$ at 40°N , the summer temperature pattern in the southern hemisphere is perfectly uniform with latitude and temperatures range from $235 + 7^{\circ}\text{K}$ at 60°S to $225 + 7^{\circ}\text{K}$ at 25°S (Figure 6). This pattern is identical to the temperature pattern during June, however, with northern and southern latitudes reversed.

C. The "Aleutian Anticyclone", December 1963

An unexpectedly warm stratosphere occurring as a regular climatological feature during winter in the general area of the Aleutian Island chain has long been recognized as the cause of a strong anticyclonic stratospheric circulation system in that area (Reference 10). Such circulation is unusual because in winter one would expect a very cold stratosphere resulting in a cyclonic circulation symmetric around the winter pole. Indeed, this cyclone exists, but in the northern hemisphere during mid-winter it is strongly disturbed and displaced by the Aleutian anticyclone. The morphology of this stratospheric warming over the North Pacific has received much attention in the past and a number of theories have been advanced attempting to explain its origin on the basis of dynamic processes (Reference 11). The satellite temperature measurements made it possible to follow the variation of mean temperatures in the lower stratosphere over this entire region throughout the winter of 1963. Figure 7a shows the temperature measured by the satellite between 40° W and 160° E and 20° N and 65° N averaged for the week from 5 to 12 December. Globally, there is practically no change from the patterns shown in Figure 6, except that the warm North Pacific region, which previously had remained at higher temperatures because it simply cooled slower than the other areas, has now actually warmed between the end of November and early December. It is centered at the end of the Aleutian Island chain and stands out clearly with temperatures of $232 \pm 7^{\circ}\text{K}$. An analysis of temperatures at the 30 mb level from conventional radiosonde observations analyzed and obtained from the Freie Universitaet Berlin for the same area and time is shown in Figure 7b for comparison. The excellent agreement in the patterns between the two maps can serve as a measure of the validity of the satellite data. As can be seen from Figures 8, 9, 11, and 12, the Aleutian warm region is a permanent feature of the entire winter from the week of 5-12 December on. However, although

temperatures within the warm center had not shown an actual increase until 5-12 December, a warm area in one form or another was present since the end of summer over the North Pacific as described above and shown in Figures 4, 5, and 6. This means that during this year the winter anomaly over the Pacific, though variable in extent during early winter, grows directly out of the summer conditions without ever reaching as low temperatures as other portions of the northern hemisphere do. Although, during early December, the system takes on a more permanent form and location and intensifies somewhat, it originated not because of a sudden heating phenomenon during winter, but simply because it refused to cool off at the end of summer. Naturally, there must be a mechanism to maintain the higher temperature during winter, while other regions at equal latitudes cool rapidly. It should be noted that those dynamic mechanisms which would have to depend on the existence of the complete winter cyclone could not explain the warm regions which already exist even before the cyclone is fully established. It might be interesting to investigate mechanisms by which the warm regions can be maintained throughout the winter by absorption of infrared radiation.

The satellite measurements show that the situation in the northern hemisphere is actually not vastly different from the southern hemisphere where a warm region over the southeastern Indian Ocean, though not quite as intense as the Aleutian one, persisted throughout the winter and then spread to make one half of the hemisphere almost 15°K warmer than the other. In the northern winter, almost a mirror image of this process occurs: the Pacific is warm and the Atlantic and Eurasia are cold, while in the south the Pacific is cold and the Atlantic and Indian Ocean areas are warm. In the north, the temperature gradients between warm and cold regions are somewhat greater (about 20°K

between 180° W and 40° W at 60° N). Of course, so far satellite data exist only for the seasonal cycle 1963/64, and the observations described here must be tested by experiments in future years.

D. Solstice, December 1963

Between November 1963 and the middle of January 1964, there is very little change from the temperature patterns shown in Figure 6. As discussed above, the Aleutian warm center becomes somewhat stronger and quite stationary during early December and, in contrast, the Atlantic and Eurasian cold regimes remained unchanged with very tight latitudinal temperature gradients and isotherms aligned with latitude during the week 15-22 January 1964 (Figure 8a). It is interesting that the temperature difference of about 15°K between 60° N and the tropical belt over the eastern portion of the northern hemisphere is less than the longitudinal temperature difference between the Aleutian warm center and the North Atlantic at 60° N. A similar situation existed in the southern hemisphere at the end of winter (Figure 5); but during the solstice, the Australian warm area did not extend to such high latitudes as the Aleutian area does. As shown in Figure 8a, the mid-latitude and tropical regions have cooled considerably; and the temperature between 25° S and 40° N is now about $218 \pm 7^{\circ}\text{K}$, while earlier temperatures in the same zone ranged near $225 \pm 7^{\circ}\text{K}$. This remarkable cooling over so wide an area is particularly significant since it precedes by about one week the occurrence of a stratospheric warming over western Asia. Instrumental degradation cannot be responsible for such a temperature decrease, since Figure 12 does indicate higher temperature again in March. Also, ever since November temperatures at high southern latitudes remained unchanged. Relatively moderate and very uniform temperature zonal temperature gradients exist at all longitudes. Temperatures at 60° S are $235 \pm 7^{\circ}\text{K}$.

Temperatures of $231 \pm 7^\circ\text{K}$ at 50°S and of $206 \pm 7^\circ\text{K}$ at 60°N (eastern portion only) are compatible with the computed temperatures of 238 and 213°K respectively for the "summer" and "cold winter" profiles (Table I). Temperatures calculated for the "tropical" profile (227°K , Table I) are about 2°K higher than those measured in the now cold mid-latitude belt ($218 \pm 7^\circ\text{K}$). Mean temperatures of $232 \pm 7^\circ\text{K}$ in the center of the Aleutian warm region measured during December suggest that the average temperature of the stratosphere in the 15 to 35 km region was about 12°K higher than that shown in the "warm winter" profile of Figure 2, which yields a mean temperature of only 229°K (Table I). Of course, such a temperature profile in this particular altitude region is merely postulated since, for example, a low average stratospheric temperature of 205°K in the altitude region from 15 to 35 km, such as shown in the "cold winter" profile, Figure 2a, could be balanced by an extraordinarily high average temperature of 300°K in the region from 35 to 60 km to produce the measured radiation temperature of 239°K . But, such a temperature profile is much less probable than the one postulated. The validity of the assumption of an average stratosphere temperature increase of 12°K between 15 and 35 km is also suggested by comparing the satellite measurements at low nadir angles ($0-40^\circ$, Figure 8a) to those at high nadir angles ($52-58^\circ$, Figure 8b). Temperatures over the Aleutian warm area are practically the same at both nadir angle ranges indicating a nearly isothermal or at least a very slowly varying temperature gradient with altitude in the region where the weighting functions $\gamma(h)$ are at their maximum (15-35 km, Figures 2b and 2c). A temperature profile such as the one mentioned above with a mean temperature of 205°K between 15 and 35 km and 300°K between 35 and 60 km would produce a difference of 9°K between the radiation temperatures measured at 0° nadir and at 58° nadir angle. Figures 8a and 8b, however, indicate no temperature difference at all over the Aleutian warm area. Thus,

one finds that the difference in the mean temperatures between 15 to 35 km level and the 35 to 50 km level cannot be excessively large, and with that restriction, a temperature increase of 10°K for the standard "warm winter" profile from 15 to 35 km follows for the North Pacific area. Similarly, one finds that there is no temperature differences for the two nadir angles over the North Atlantic and Northern Europe (Figures 8a and 8b) which agrees well with the calculated differences of 1°K for the "cold winter" profile. The larger temperature differences over the tropics--the 220°K isotherm is about 10° further north in Figure 8b than in Figure 8a--indicate the rapid temperature increase with altitude above 15 km and agree well with the computed difference of 4°K for the "tropical" profile (Table I); while the calculated values of 238 and 240°K for "high latitude summer" (Table I) agree well with the observed temperatures (-7° correction) and temperature differences between 50° and 55° S.

This picture has changed considerably during late January (Figures 11a and 11b) where temperature differences at mid-latitudes and in the tropics over the entire eastern hemisphere are as high as or exceed the differences observed previously within the tropics. Such large differences exceeding 5°K extend particularly into North Africa, the eastern Mediterranean and the Near East (Figures 11a and 11b). This indicates that neither the "tropical" nor the "summer" temperature profiles (Figure 2a) apply in this case. In that area, temperatures at 15 km must be somewhat higher than those given by the "tropical" profile; and there must be a pronounced increase of temperature with altitude resulting in a very warm upper stratosphere, i.e. a very strong vertical temperature gradient between the lower and upper stratosphere. It is significant that this change has occurred over the area into which the sudden warming, described below, has moved in its decaying stages.

E. Sudden Warming, January 1964

The type of temperature measurement from a satellite described here was expected to be most useful for the detection of the occurrence and the observation of the behavior of stratospheric warmings. These warmings were first observed over Berlin by Scherhag (Reference 12) and have since then been the subject of intensive observation and analysis (Reference 13). The sudden warmings have now been observed almost every year during the northern hemisphere winter and, during their occurrence, the lower stratosphere over a limited area may be heated by as much as 30°K within a few days. Causes for such warmings have thus far not been explained. In contrast to the Aleutian warm center described above, the sudden warmings show no regularity in their time and location of occurrence. In order to be detectable by the TIROS radiometer, the warming must occur at altitudes between 15 and 35 km, or, if it occurs at other levels, it must be unproportionally intense. Calculations based on the "warm winter" temperature profile of Figure 2a show that a uniform temperature increase of 12°K between 15 and 35 km will increase the radiation temperature by 10°K , while a similar change of the temperature profile between 34 and 44 km will cause a rise in the radiation temperature of less than 1°K .

A number of small and weak warmings occurred over America and Europe during December 1963 and January 1964, but those did not penetrate to altitudes below 30 km (Reference 14). Therefore, they could not be detected by the satellite. During the last week of January (22-29), however, a warming of apparently moderate intensity occurred over the region of the Caspian Sea, extending between the Himalayan Mountains and the Black Sea (Figure 9a). Radiation temperatures over that area have increased by about 8°K over the previous week (Figure 8a). During that week (15-22 January), there was practically no indication of any

disturbance in the perfect latitudinal temperature structure over that region, except perhaps for a very small area over Iran where a temperature increase of about 2-3 degrees could be observed; but in the high nadir angle measurements, there is an indication of increased temperatures over South Central Asia (Figure 8b) inferring that the subsequent warming might have originated in the upper stratosphere (above 30 km) in that area. Unfortunately, the warming developed in an area where no conventional meteorological data at these altitudes are available, and the satellite observations provide the only method of analyzing the event. Furthermore, even the satellite observations are limited in coverage, since this area is located near the data gap over the central Soviet Union which exists because of the particular geometry of the data readout stations for TIROS (see above). The satellite data were, therefore, analyzed for individual days of 22, 24, 25, 26, 27, and 29 January. These daily analyses showed that the temperatures within the warm center were as high as $230 + 7^{\circ}\text{K}$ on 29 January, but because they extended only over very small regions and because of the motion of the center from day to day, these high temperatures became obscured in the weekly averages (Figure 9a). The first definite indication of the warming occurs on 22 January, where a small and relatively weak warm center of $225 + 7^{\circ}\text{K}$ appears over Pakistan, Afghanistan and Eastern Iran. This is already a few degrees higher than the average temperature over the same area for the preceding week of 14-22 January (Figure 8a). Two days later on 24 January, the warm region had spread out somewhat to the north, and the center had also moved in that direction but had not significantly intensified. On 25 January, temperatures of $225 + 7^{\circ}\text{K}$ range over the entire middle East extending as far eastward as central China. The center is now just east of the Caspian Sea and has just barely reached a temperature of $230 + 7^{\circ}\text{K}$. On 26 January,

the same situation prevails with the center becoming slightly warmer and larger. On 27 January, the center has grown considerably larger and temperatures of $230 + 7^{\circ}\text{K}$ extend over an area of at least 30° longitude and 10° latitude northeast of the Caspian Sea. The $225 + 7^{\circ}\text{K}$ isotherm has advanced to a latitude of 50° N, causing a tremendously tight temperature gradient over northern Europe where temperatures increase by more than 20°K from southern Norway to the Black Sea. Due to the warming, isotherms have been tilted to follow a course from southeast to northwest instead of the perfect eastwesterly direction still prevailing on 22 January. Finally, on 29 January a warm center extending over 10° great circle arc with temperatures of $230 + 7^{\circ}\text{K}$ stretches from the Black Sea eastward to China. One 225° isotherm now runs east-west along the 40th parallel between 40° E and 80° E. The other runs southwest to northeast from the Black Sea to about 50° E and 55° N. The center is located near 65° E and 50° N. This situation is summarized in Figure 10 which shows that on 27 January the radiation temperatures had increased by 15°K over the averages for the week 9-15 January near the center and that the periphery of the warming extended as far west as the North Sea, and the Atlantic and as far south as North Africa and Arabia. Figure 11a shows that during the week 31 January to 8 February the warming had passed its climax. Rather homogeneous temperature patterns with latitude return over northern Europe and eastern Asia, but south of 40° N a broad warm area of about $223 + 7^{\circ}\text{K}$ now covers the entire region between 40° N and 25° S latitude and 110° W and 80° E longitude (Figure 11a). This means that the mid-latitude belt which had cooled so drastically before the warming had been restored close to its normal temperature of about $223 + 7^{\circ}\text{K}$ between 25° S and 40° N. Figures 8, 9, and 11 show that the Aleutian warm center had remained undisturbed during the entire period of the warming. On 30 January, the warming was

detected by a radiosonde ascent over Berlin, the only one available for this analysis (Reference 15). This radiosonde temperature profile, when compared to a prewarming profile shows that the warming over Berlin occurred primarily above 30 km. For the week of 22-29 January, temperatures at high nadir angles are about 5°K higher than at low nadir angles not only over the warm center, but also extending far beyond the center, particularly along the southern and western periphery of the warming (Figures 9a and 9b). This means that over the center temperatures have increased not only in the lower stratosphere but more so in the upper stratosphere. The much greater extent of the warming in the high nadir angle temperature patterns compared to the low nadir angle patterns suggested that along the western and southern periphery the warming occurred only in the upper stratosphere. This confirms the above mentioned radiosonde observation over Berlin. Since the much larger warming (13°K) in the center would require an unreasonably large temperature if the warming were confined to altitudes above 30 km, and since such a strong vertical temperature gradient would be clearly noticeable as a much greater temperature increase at the larger nadir angles, it must be concluded that the warming near the center penetrated to much lower altitudes where the Ψ functions are at maximum. If the warming occurred uniformly at altitudes from 15 to 35 km, a temperature increase of about 15°K would satisfy the radiation measurements. Such an increase is quite commensurate with a moderate stratospheric warming.

F. Equinox, March 1964

The global temperature structure undergoes a major change during the period from early February (Figure 11a) to the week of 18-25 March shown in Figure 12. The steep zonal winter time temperature gradients at high northern latitudes, particularly over the eastern hemisphere as well as the zonal summer pattern in the southern hemisphere have disappeared. The southern hemisphere

has cooled considerably, and parts of the northern hemisphere have warmed. This results again, as during the September equinox, in an almost constant temperature over the entire quasi-globe. In fact, temperature gradients, longitudinally or latitudinally are even shallower than during September. Over the eastern Pacific, there is no temperature gradient at all between 60° S and 60° N, with temperatures of about $223 \pm 7^{\circ}\text{K}$ prevailing at all latitudes. As the southern hemisphere cools, a temperature gradient along 60° S seems to develop similarly as during the previous winter. The South Indian and Atlantic Oceans are now about 5°K warmer than the South Pacific.

In the northern hemisphere near 60° the North Atlantic and northeast North America have warmed rapidly by about 20°K since February, while the region east of the Black Sea, where the sudden warming occurred in January, has returned to its pre-warming winter temperatures of $217 \pm 7^{\circ}\text{K}$. Temperatures in the Aleutian region have remained practically constant throughout the winter and are still at about $228 \pm 7^{\circ}\text{K}$. This produces temperature differences of about 10°K between the Atlantic and Pacific warm regions and central Asia at 50° N. That is the largest temperature difference found during this equinox (Figure 12). Since these data have been reduced only very recently, there has not yet been an adequate opportunity to analyze the January to March transition as thoroughly as the June to October period. Such an analysis will be made in the future.

IV. CONCLUSIONS AND SUMMARY

Satellite measurements of emitted radiation in the 15 micron carbon dioxide band have demonstrated that mean temperatures in the lower stratosphere can be mapped on a global scale. By comparing measurements at high and low nadir angles, a qualitative inference can be made about the vertical temperature

gradient between the lower and upper stratosphere. Analysis of global temperature patterns from June 1963 to March 1964 revealed that temperature patterns in both hemispheres remain relatively undisturbed during summer. These patterns are oriented very precisely along latitude circles with the temperature maximum occurring at the summer pole. Near maximum temperatures are reached in the southern summer about one month after the equinox. After that, temperatures increase only slightly through the solstice and remain high until the next equinox. The northern summer could only be analyzed through its peak and declining phases, June to September 1963. Temperatures decline very slowly during the first two months following the solstice. Then, a rapid decline occurs just before the equinox. During both equinoxes, temperatures were relatively uniform and differences of about 10-15°K may exist both with latitude and longitude. Winter temperature patterns in both hemispheres exhibit strong temperature gradients between the pole and 40°, but a completely uniform pattern never exists in either winter hemisphere. A fairly uniform region with temperatures generally around 230°K extends between 25° latitude of the summer hemisphere and 40° latitude of the winter hemisphere during solstice. The satellite measurements not only permitted for the first time a continuous analysis of the southern hemisphere from June 1963 to March 1964 up to a latitude of 65° S, but also demonstrated the usefulness of uniform and continuous data coverage over the entire quasi-globe. A warm area over the Indian Ocean, though initially small, seems to play a similar role in the southern winter as the Aleutian warm center during the northern winter. During winter 1963, this warm region grew out of a disturbance in the isotherms during June and finally divided the entire stratosphere of the winter hemisphere into a "warm" and "cold" portion with the warm portion located between Africa and Australia. Temperature differences between these warm and cold

areas amounted to about 15°K and disappear with the warming of the South Pacific area during late October, giving way to the homogeneous summer pattern. Similarly, there is no homogeneous winter pattern in the northern hemisphere. A large region over the North Pacific does not cool off as rapidly after the equinox as the rest of the stratosphere. Just before the solstice, this region becomes well established and intensifies in the area where the Aleutian anticyclone is usually found.

The morphology of a stratospheric warming over southwestern Asia and its penetration to Europe was observed by the satellite indicating that heating of possibly 20°K penetrated down to at least 20 km over the center of the warming, but at the periphery warming of perhaps somewhat greater magnitude remained at altitudes above 30 km. The persistent climatological inhomogeneities of warm cells over both winter hemispheres lead to the speculation that during winter the stratospheric temperatures may be influenced by radiation from underlying surfaces, while during summer solar heating is dominant.

A study was also made of the effect of how high altitude clouds on the measured temperatures, since the weighting functions (Figure 2b) are not negligible at 10 km. The result indicated that very large and high cloud systems such as hurricanes do decrease the measured temperatures by as much as 10°K if the clouds reach above 10 km and by less than 4°K if the clouds, filling the field of view are at 6 km; but it was shown that such effects are only isolated and are averaged out by the weekly analyses which formed the basis for this investigation.

ACKNOWLEDGMENTS

Experiments resulting in findings such as the ones presented here always require the efforts of many hundreds of dedicated individuals. We gratefully acknowledge the contributions of those who have contributed to the success of the TIROS VII experiments. We are particularly indebted to Mr. Robert Hite and his team for the computational efforts in reducing the vast amount of radiation measurements to the maps presented here.

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FIGURE CAPTIONS

- Fig. 1(a) Effective spectral response of the TIROS VII 15μ channel as a function of wavelength.
- Fig. 1(b) Average quasi-global equivalent blackbody temperatures vs. time. The heavy dashed curve indicates the derived apparent degradation in the instrumental response.
- Fig. 2(a) Typical temperature profiles based on proposed supplements to the "U. S. Standard Atmosphere 1962" for 60° North summer, 60° North winter (warm and cold) and 15° North. The "warm" and "cold" temperature profiles for 60° N ("high latitude winter") can be considered typical at these latitudes depending on the state of the stratosphere in these regions. The supplements to the U. S. Standard Atmosphere 1962 are in the process of preparation by the U. S. Committee for Extension of the Standard Atmosphere and were summarized by Cole, et al (Reference 16).
- Fig. 2(b) Weighting functions $\psi(h)$, applying to the measured outgoing radiance \bar{N} ; nadir angle = 0° .
- Fig. 2(c) Weighting functions, $\psi(h)$, applying to the measured outgoing radiance \bar{N} ; nadir angle = 58° .
- Fig. 3(a) Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 19-25 June 1963; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 3(b) Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 19-25 June 1963; nadir angle 52° - 58° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 4 Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 11-18 September 1963; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 5 Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 25 September-1 October 1963; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.

FIGURE CAPTIONS(Continued)

- Fig. 6 Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 20-26 November 1963; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 7(a) Map from the North Pacific to the North Atlantic of 15μ equivalent blackbody temperatures averaged over the week 5-12 December 1963; nadir angle 0° - 40° .
- Fig. 7(b) Map from the North Pacific to the North Atlantic of 30 mb air temperatures measured by radiosonde balloons averaged over the week 5-12 December 1963 (Reference 16).
- Fig. 8(a) Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week of 15-22 January 1964; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 8(b) Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 15-22 January, 1964; nadir angle 52° - 58° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 9(a) Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 22-29 January, 1964; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 9(b) Regional map of 15μ equivalent blackbody temperatures averaged over the week 22-29 January 1964; nadir angle 52° - 58° . The effects of a stratospheric warming over Eastern Europe are illustrated. No essential change in the temperatures occurred in other areas of the quasi-globe relative to Figure 8(b).
- Fig. 10 Regional map of the differences between the 15μ equivalent blackbody temperatures measured on 27 January 1964 and those averaged over the week 9-15 January; nadir angle 0° - 40° . The effects of a stratospheric warming over Eastern Europe are illustrated.

FIGURE CAPTIONS (Continued)

- Fig. 11(a) Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 31 January-8 February 1964; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 11(b) Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 31 January-8 February 1964; nadir angle 52° - 58° . Radiation data cannot be obtained outside the area enclosed by the dashed border.
- Fig. 12 Quasi-global map of 15μ equivalent blackbody temperatures averaged over the week 18-25 March, 1964; nadir angle 0° - 40° . Radiation data cannot be obtained outside the area enclosed by the dashed border.

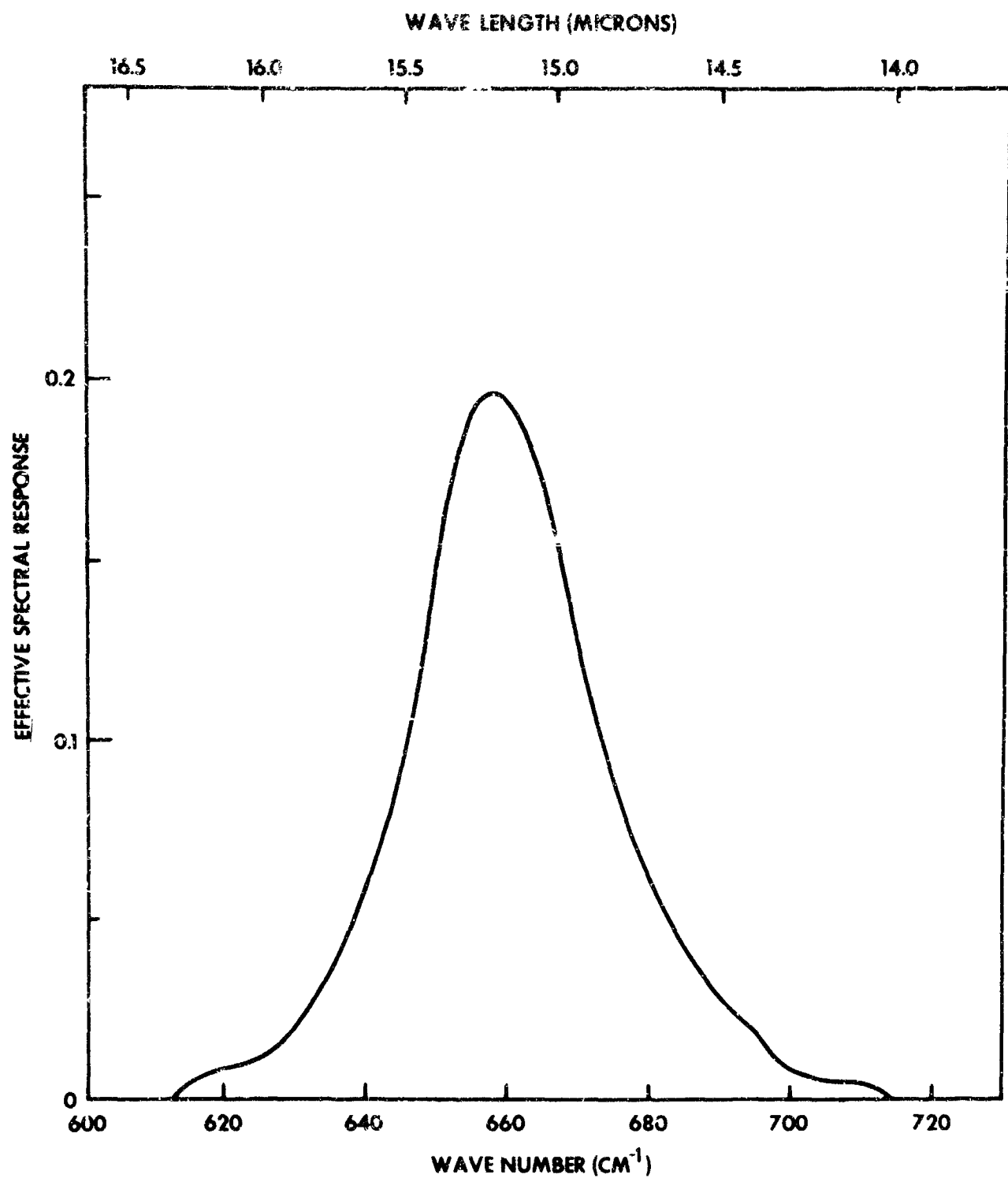


Figure 1a

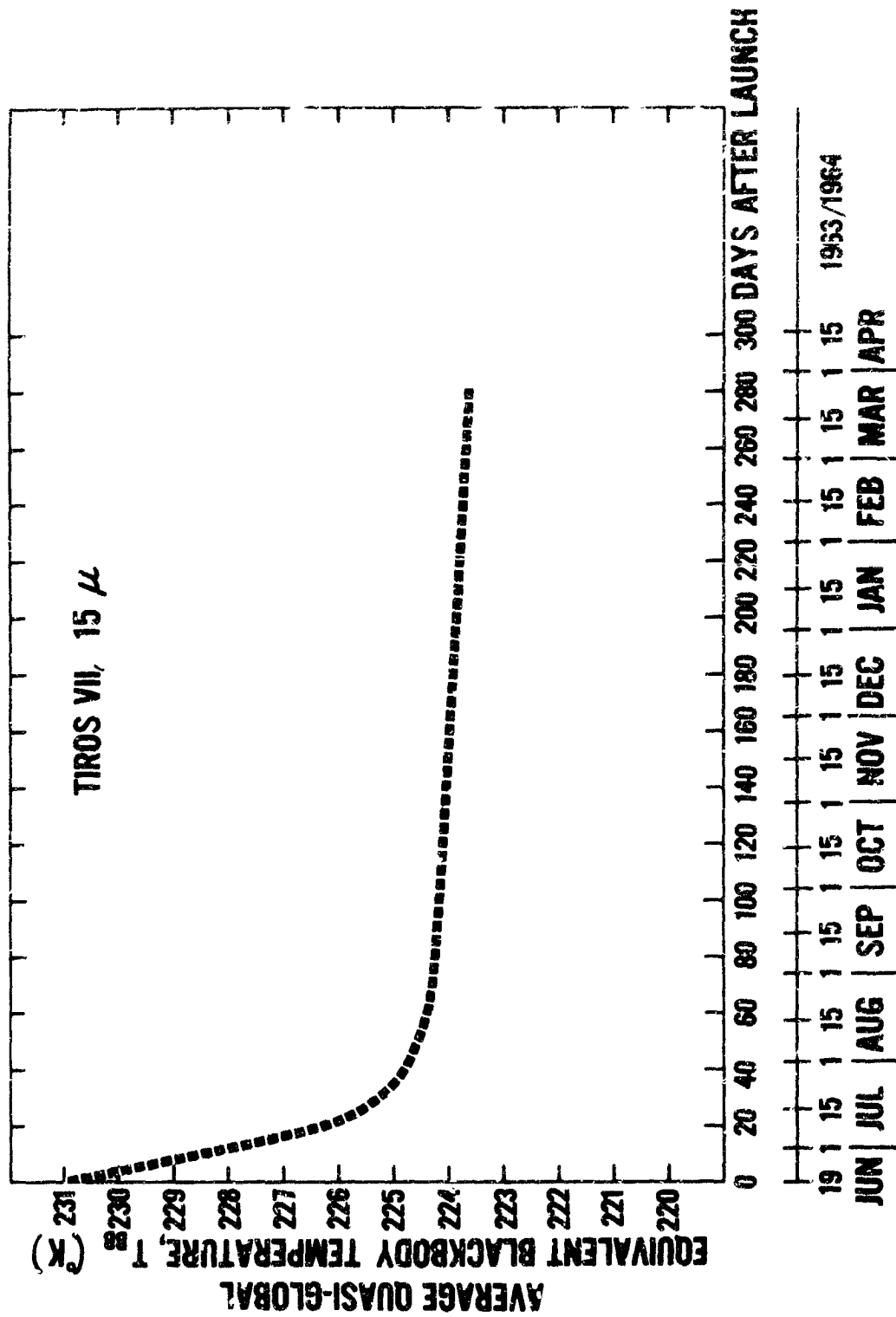


Figure 1b

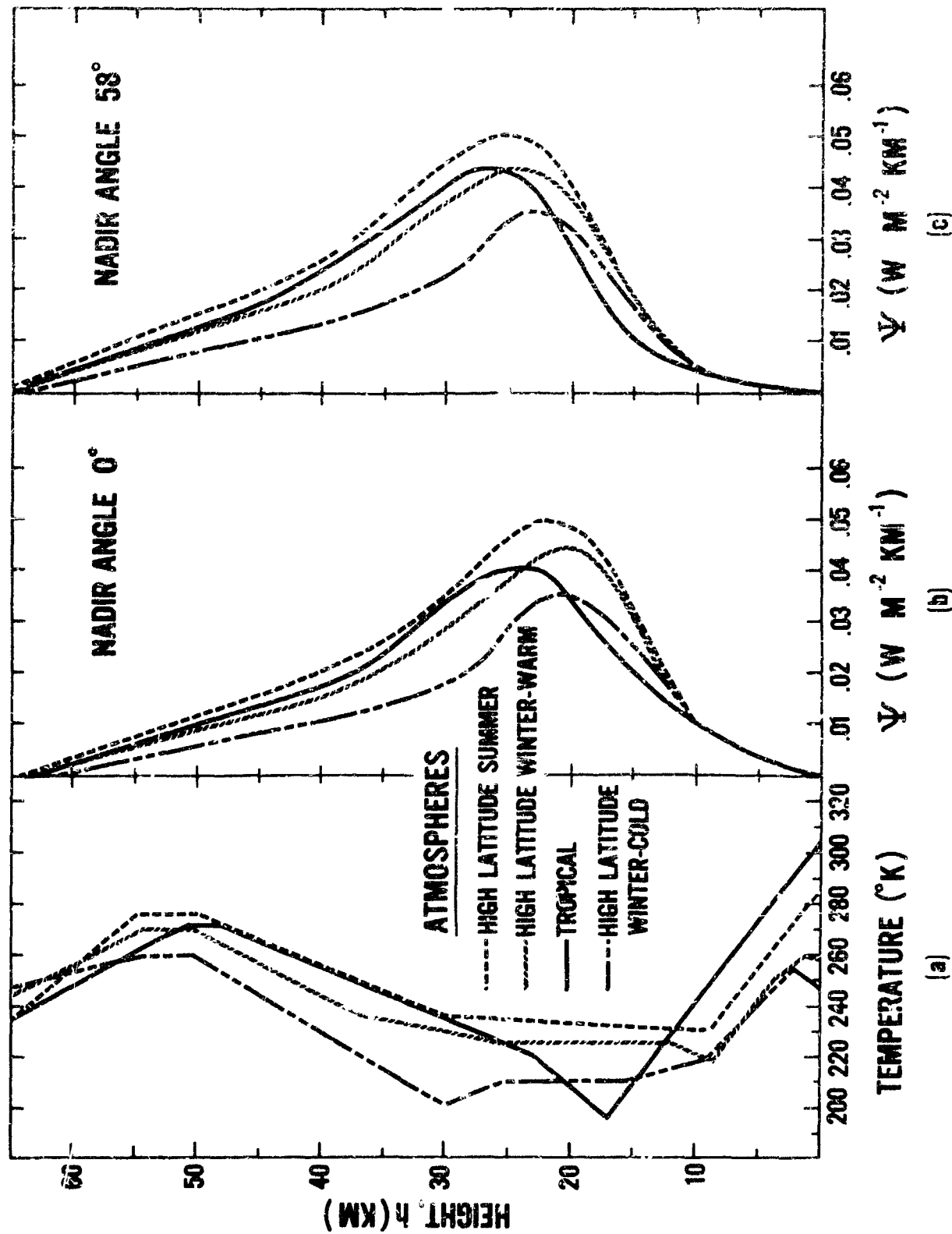


Figure 2

TIROS VII, 15 μ T_{BB} [°K]
 NADIR ANGLE 0-40°
 19-25 JUNE 1963

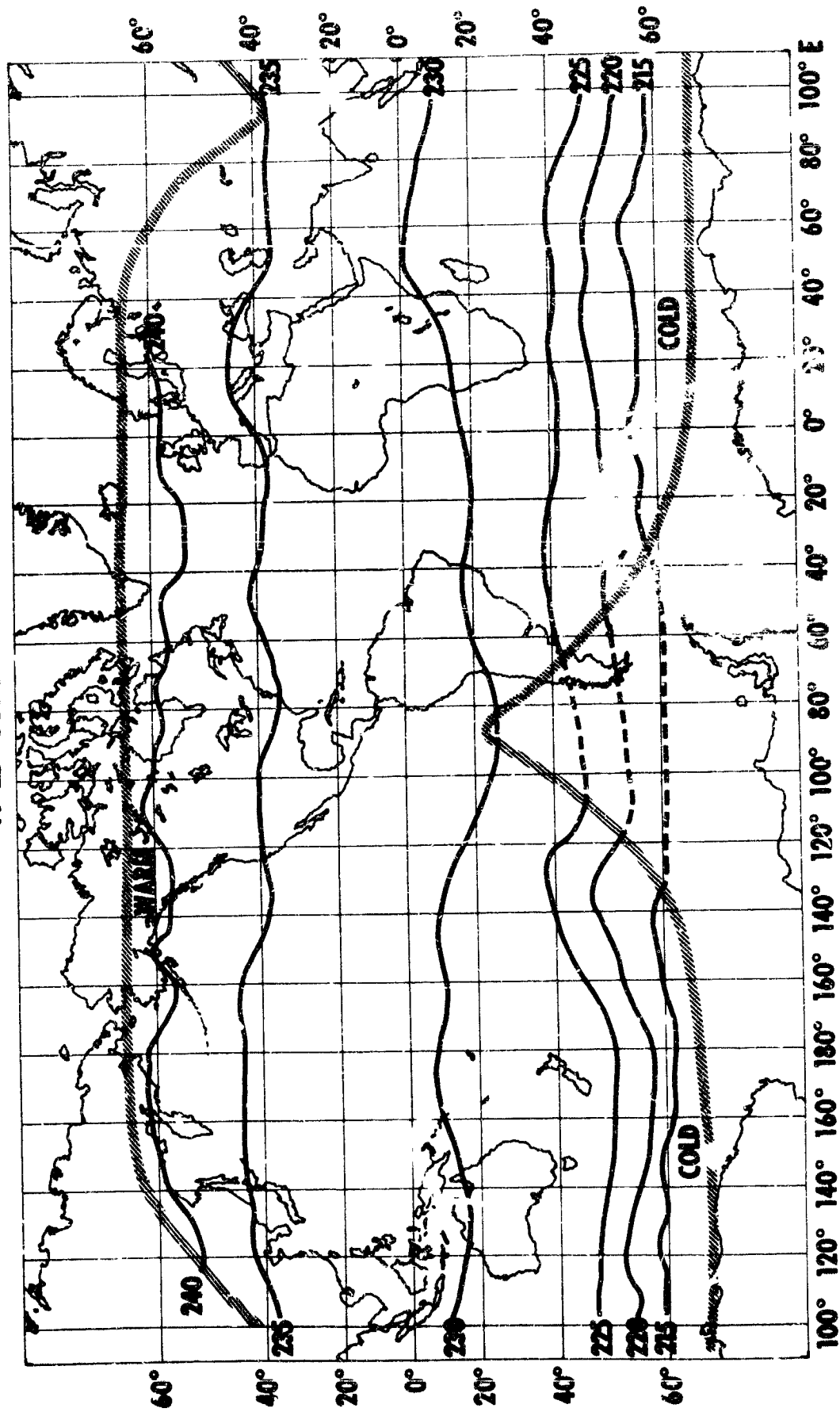


Figure 3a

TIROS VII, 15 μ T_B [°K]
 NADIR ANGLE 52-58°
 19-25 JUNE 1963

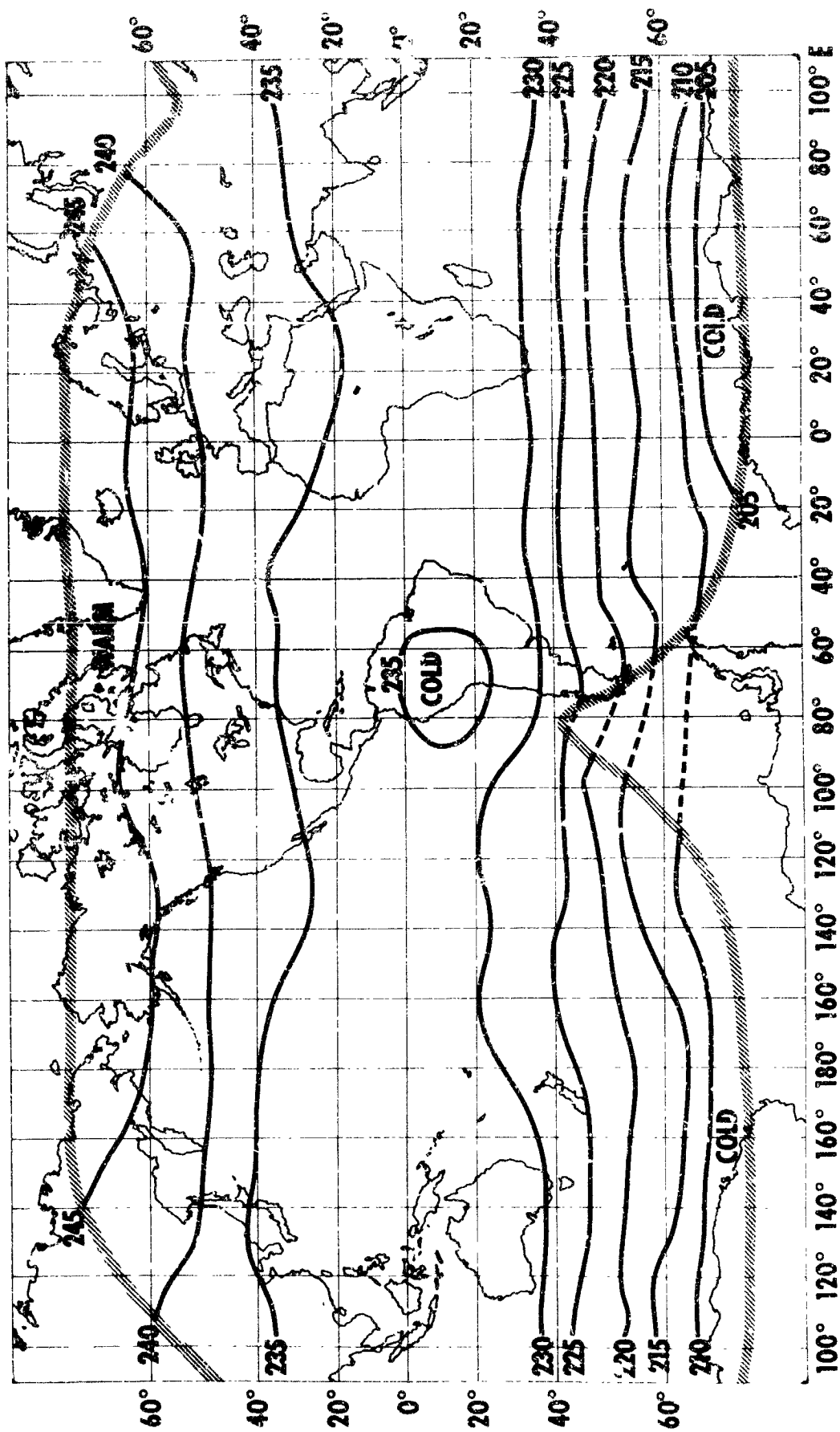


Figure 3b

TIROS VII, 15μ T_{BB} [$^{\circ}K$]
 NADIR ANGLE 0-40°
 11-18 SEPTEMBER 1963

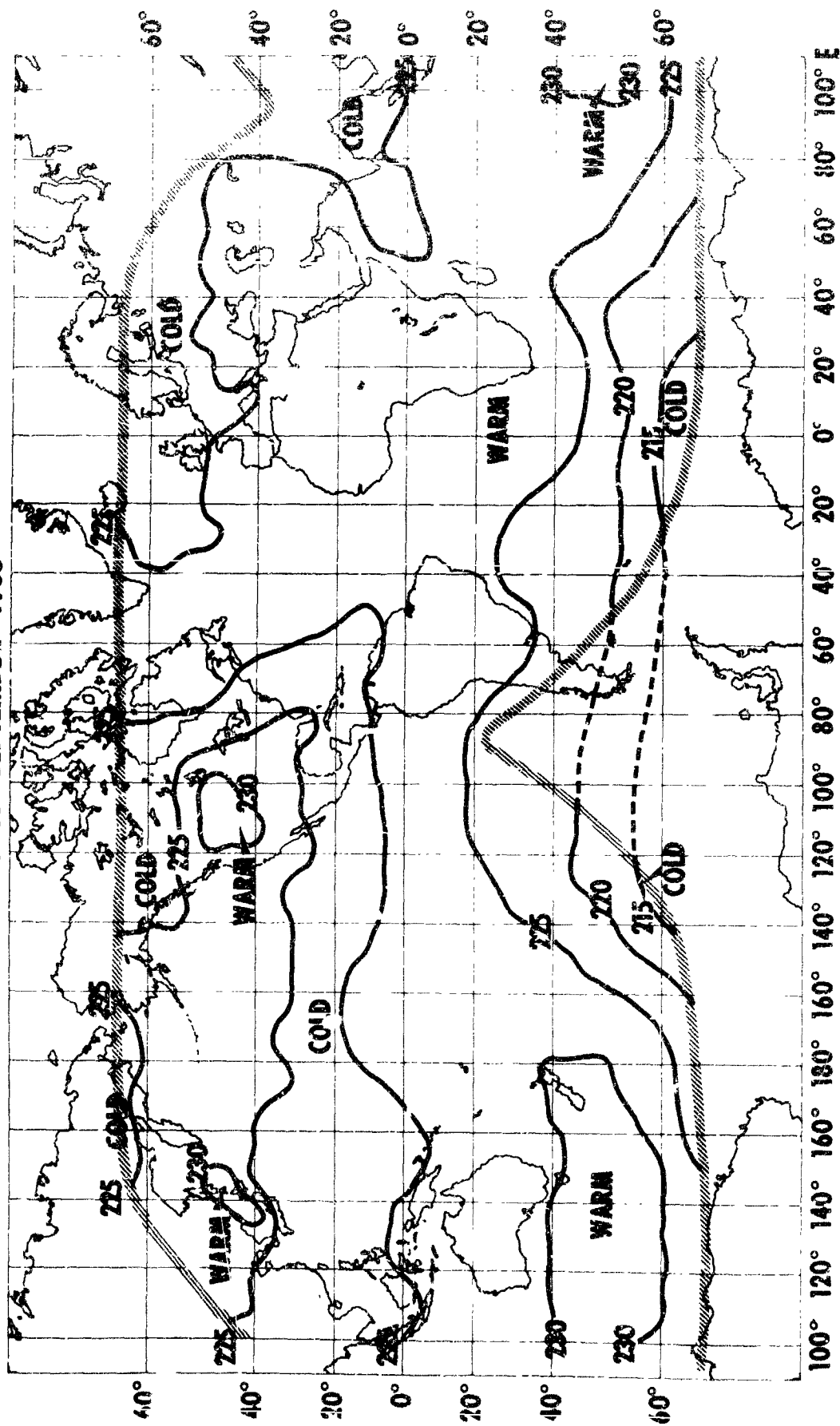


Figure 1

TIROS VII, 15 μ T_{BB} (°K)
 NADIR ANGLE 0-40°
 25 SEPTEMBER-1 OCTOBER 1963

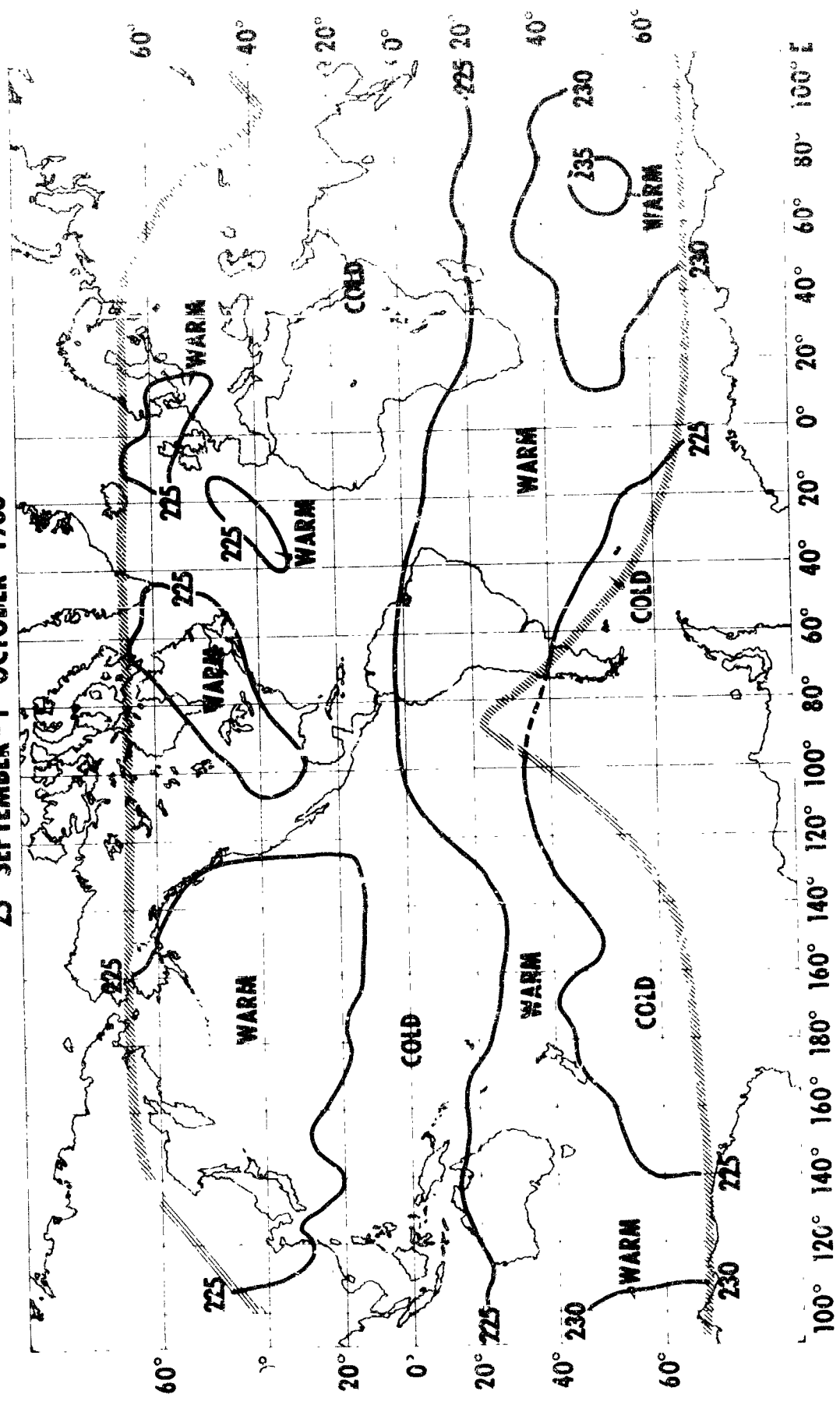


Figure 5

TIROS VII, 15μ T_{BB} ($^{\circ}K$)
 NADIR ANGLE 0-40°
 20-26 NOVEMBER 1963

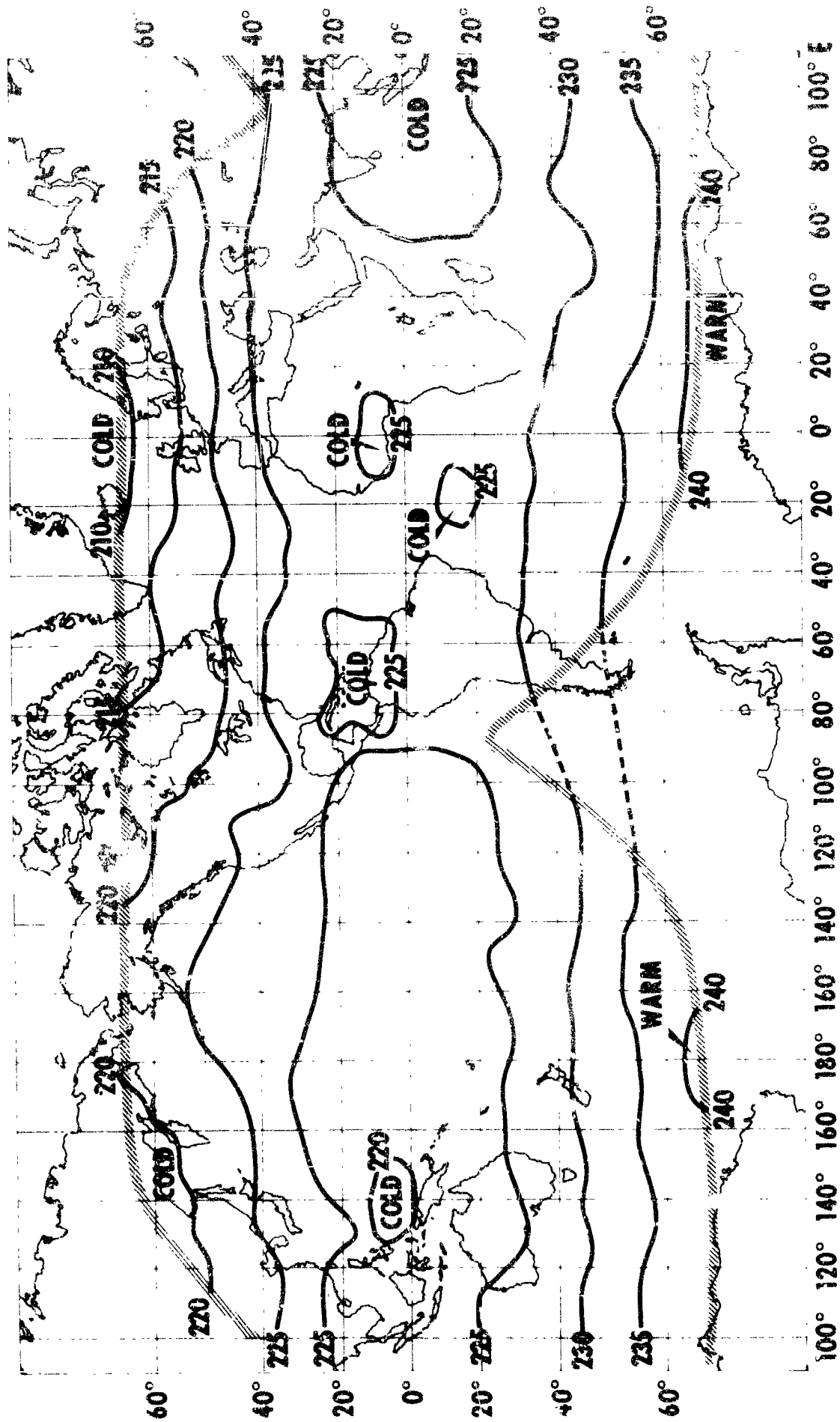


Figure 6

TIROS VII, 15μ T_{BB} (°K)

NADIR ANGLE 0-40°

5-12 DEC, 1963

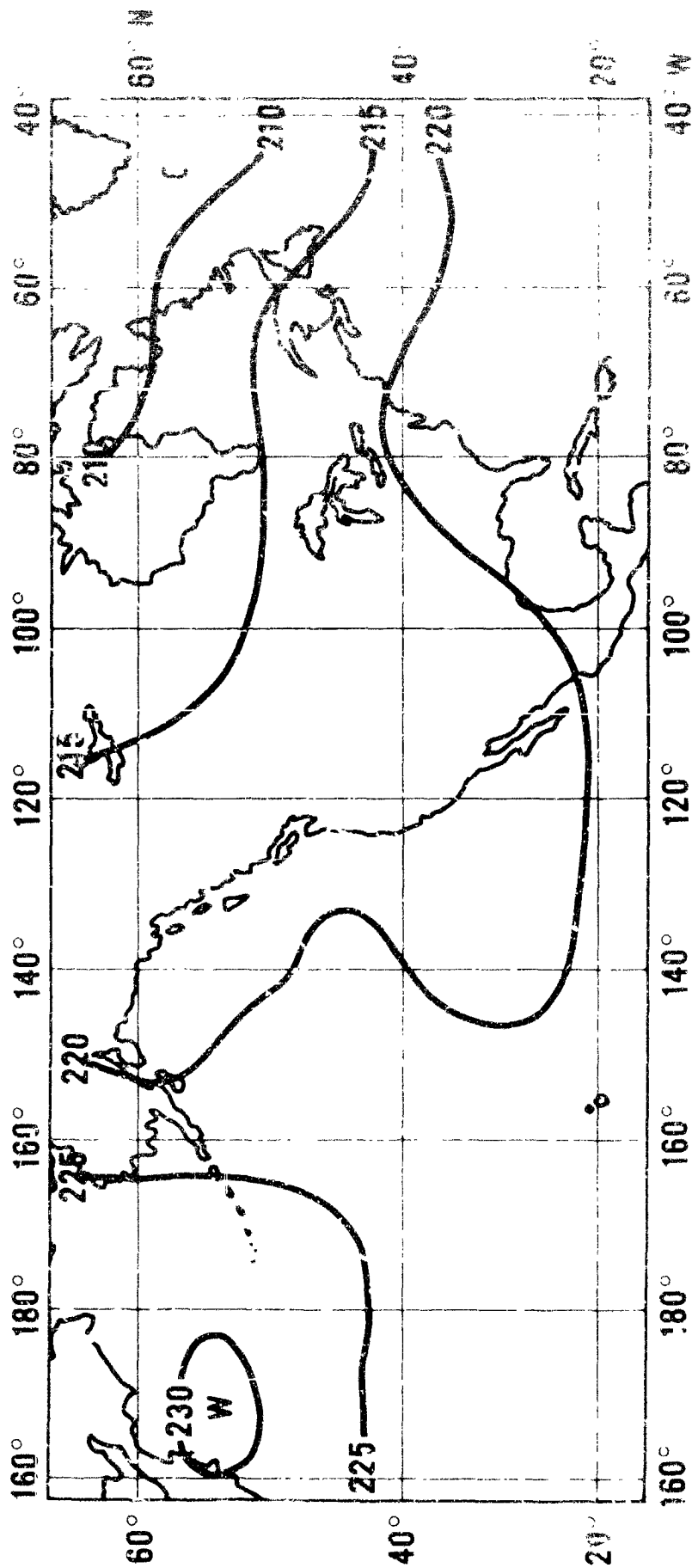


Figure 7a

AVERAGED 30 MILLIBAR ISOTHERMS, (°K)

1200 GMT

2-12 DECEMBER, 1963

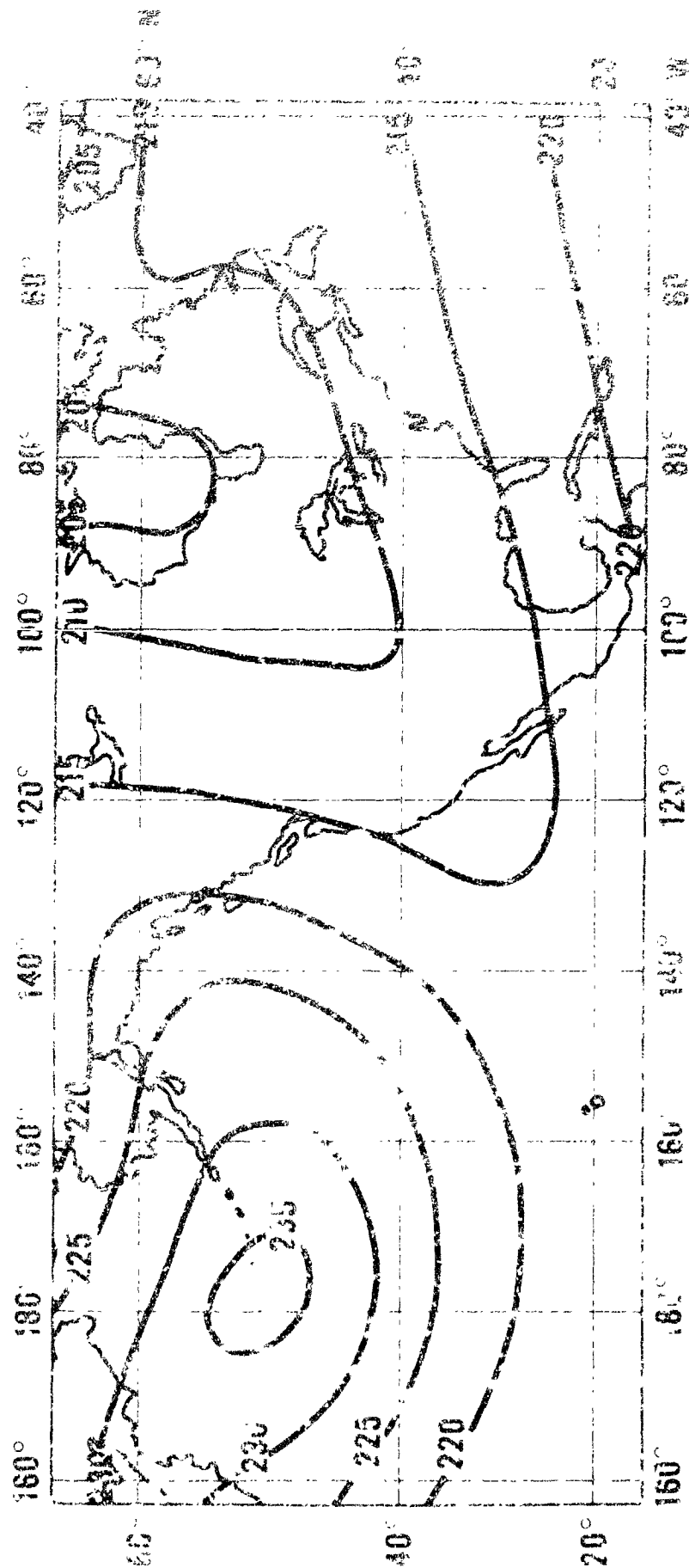


Figure 7b

TIROS VII, 15μ T_{BB} [$^{\circ}$ K]
 NADIR ANGLE 0-90°
 15-22 JANUARY 1964

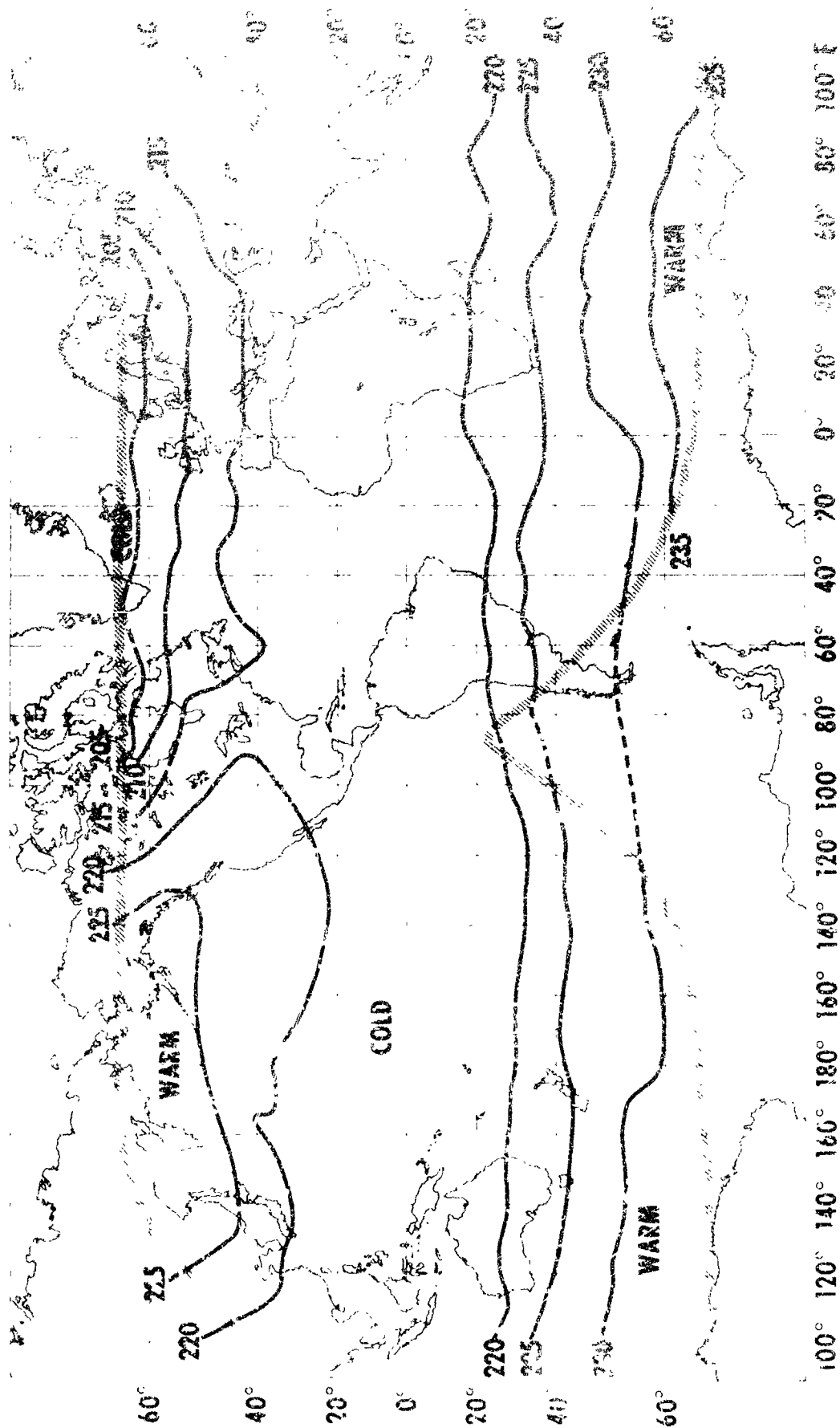


Figure 8a

TIROS VII, 15 μ T_{SB} (°K)

NADIR ANGLE 52-58°

15-22 JANUARY 1964

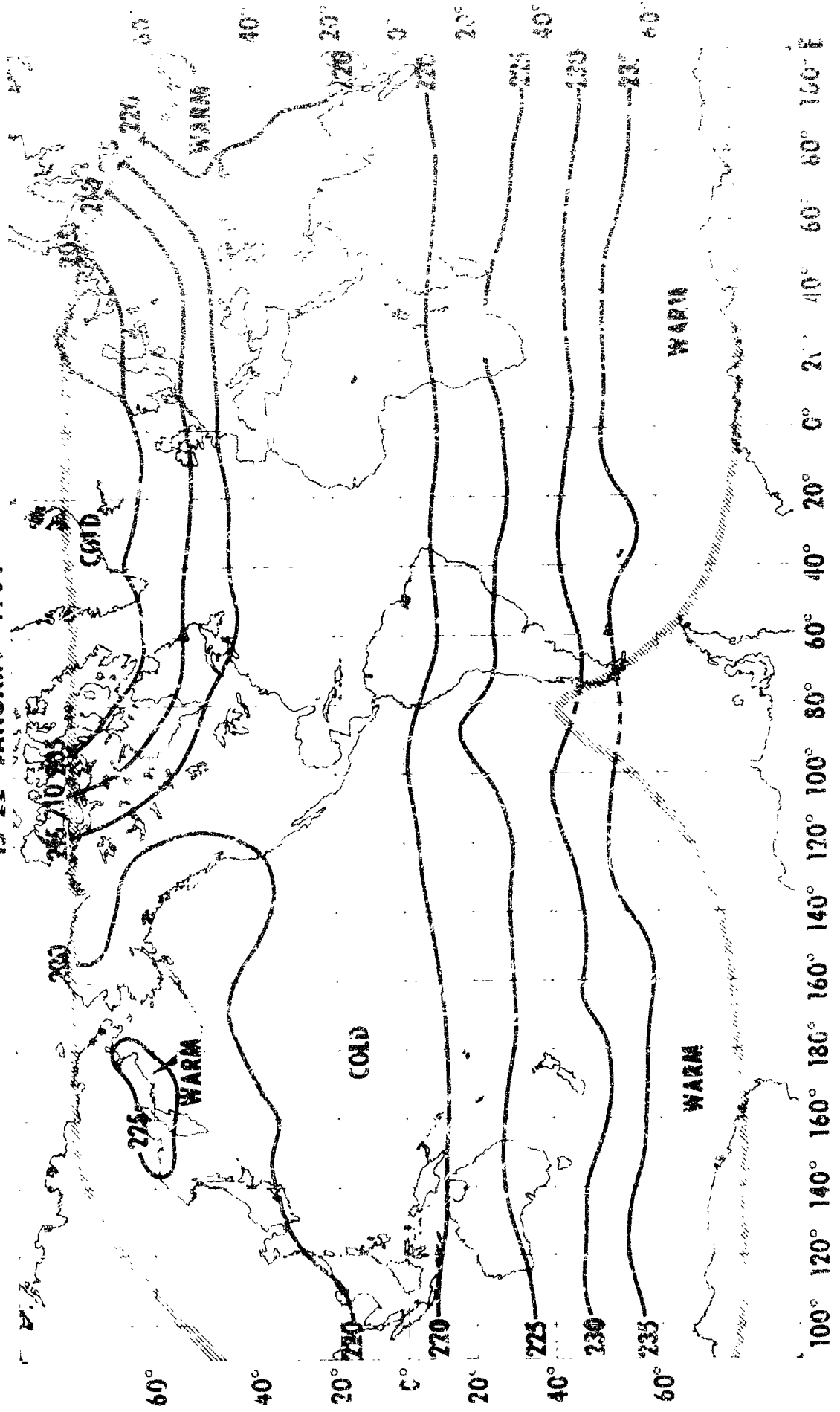


Figure 8b

TIROS VII, 15 μ T_{BB} ($^{\circ}$ K)
 NADIR ANGLE 0-40°
 22-29 JANUARY 1964

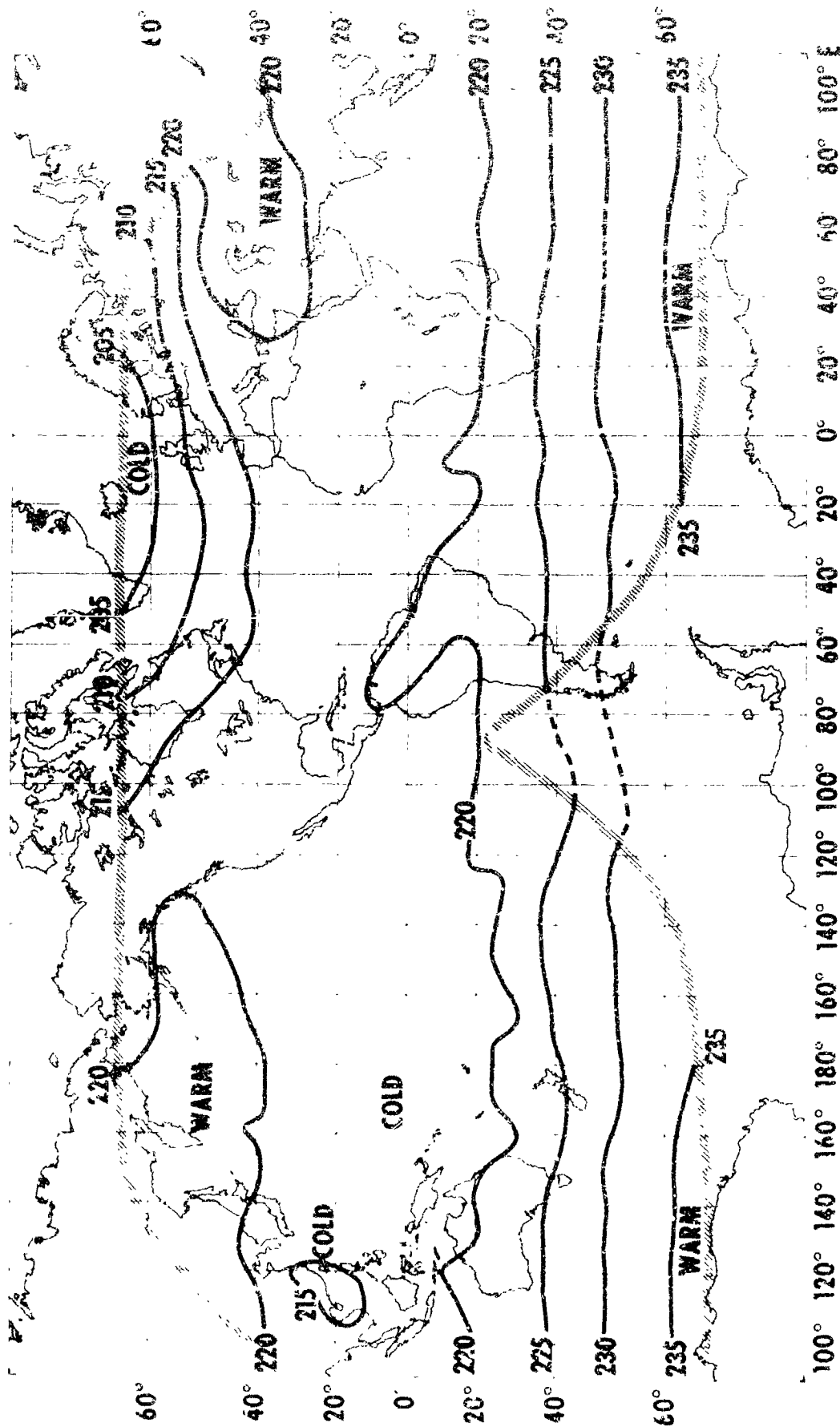


Figure 9a

TIROS VII, 15 μ T_{BB} [°K]
 NADIR ANGLE 52-58°
 29-29 JANUARY 1964

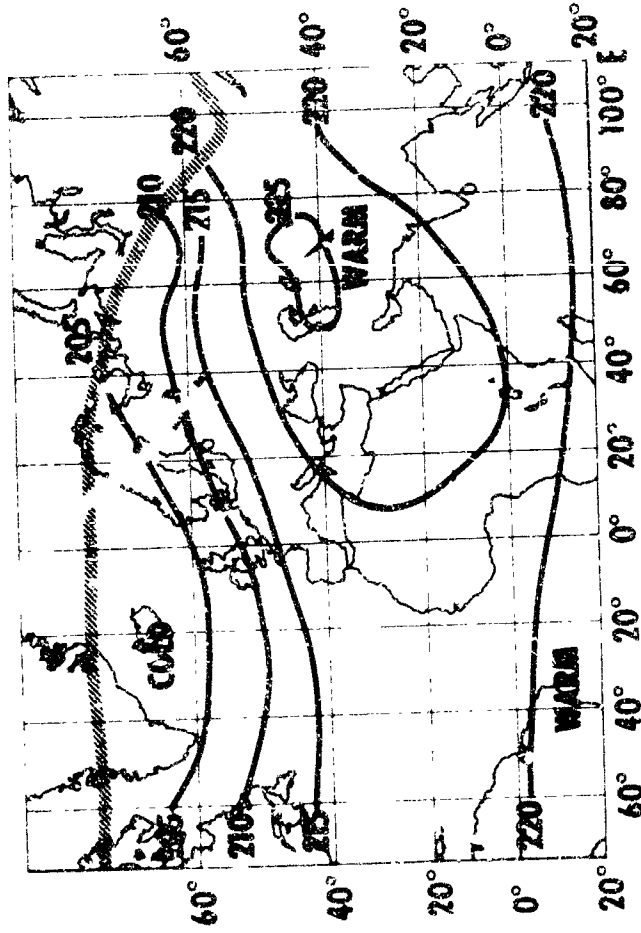


Figure 9b

TIROS VII, 15 μ CHANNEL
STRATOSPHERIC TEMPERATURE CHANGE ($^{\circ}$ K)
9-15 JAN 1964 TO 27 JAN 1964

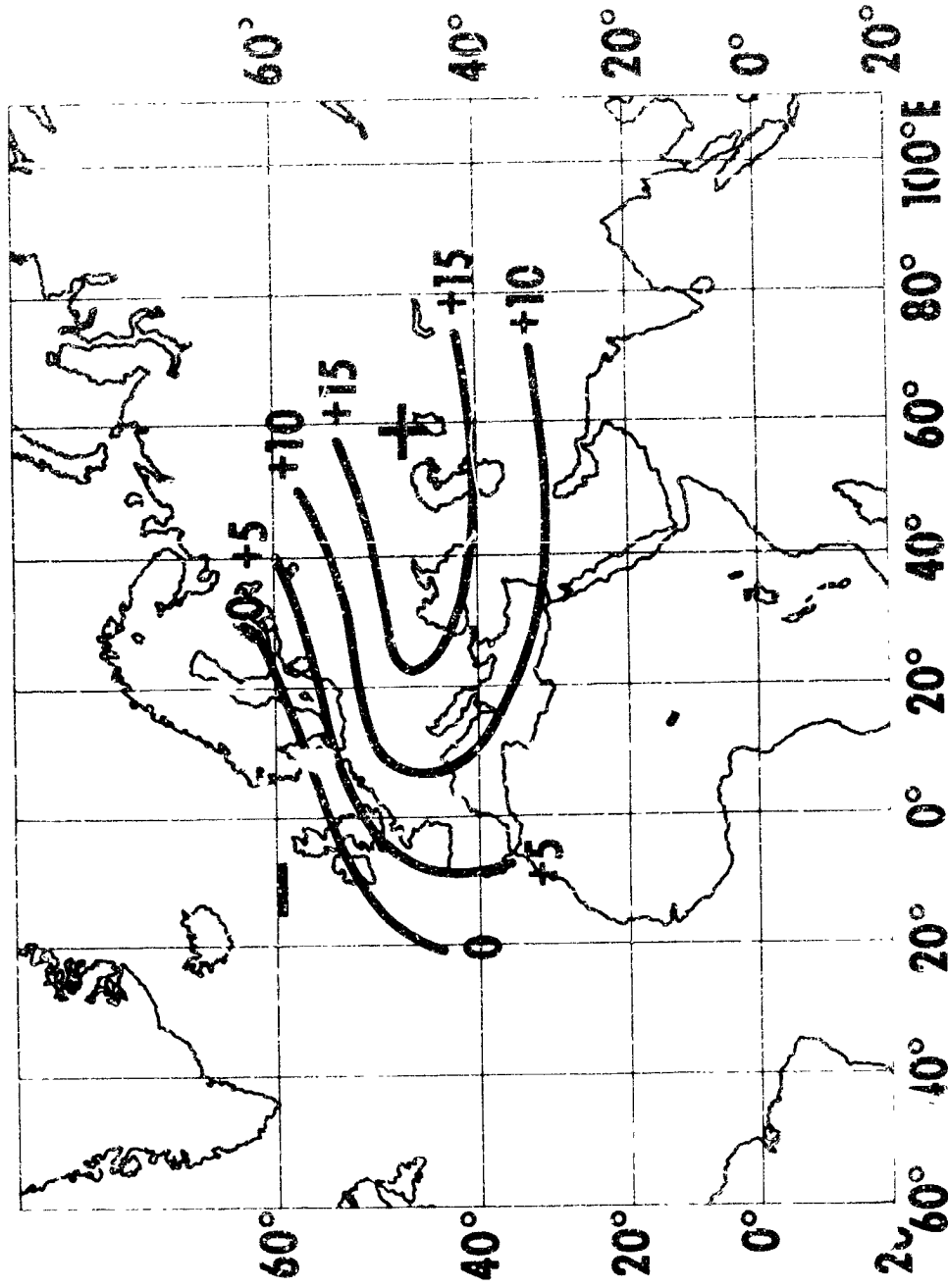


Figure 10

TIROS VII, 15μ T_{BB} ($^{\circ}K$)
 NADIR ANGLE 0-40°
 31 JANUARY - 8 FEBRUARY 1964

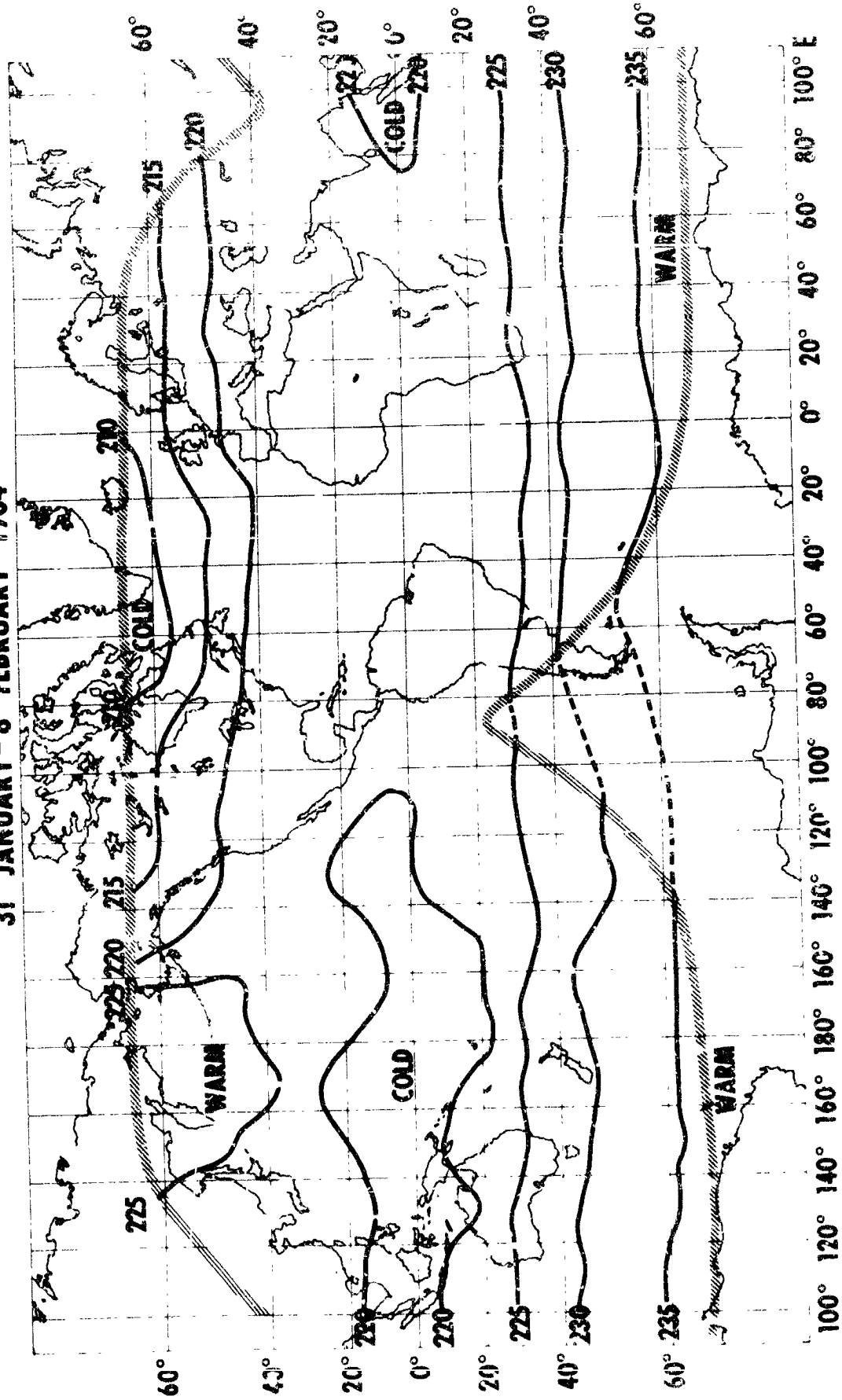


Figure 11a

TIROS VII, 15 μ T_{BB} [$^{\circ}$ K]
 NADIR ANGLE 52-58 $^{\circ}$
 31 JANUARY - 8 FEBRUARY 1964

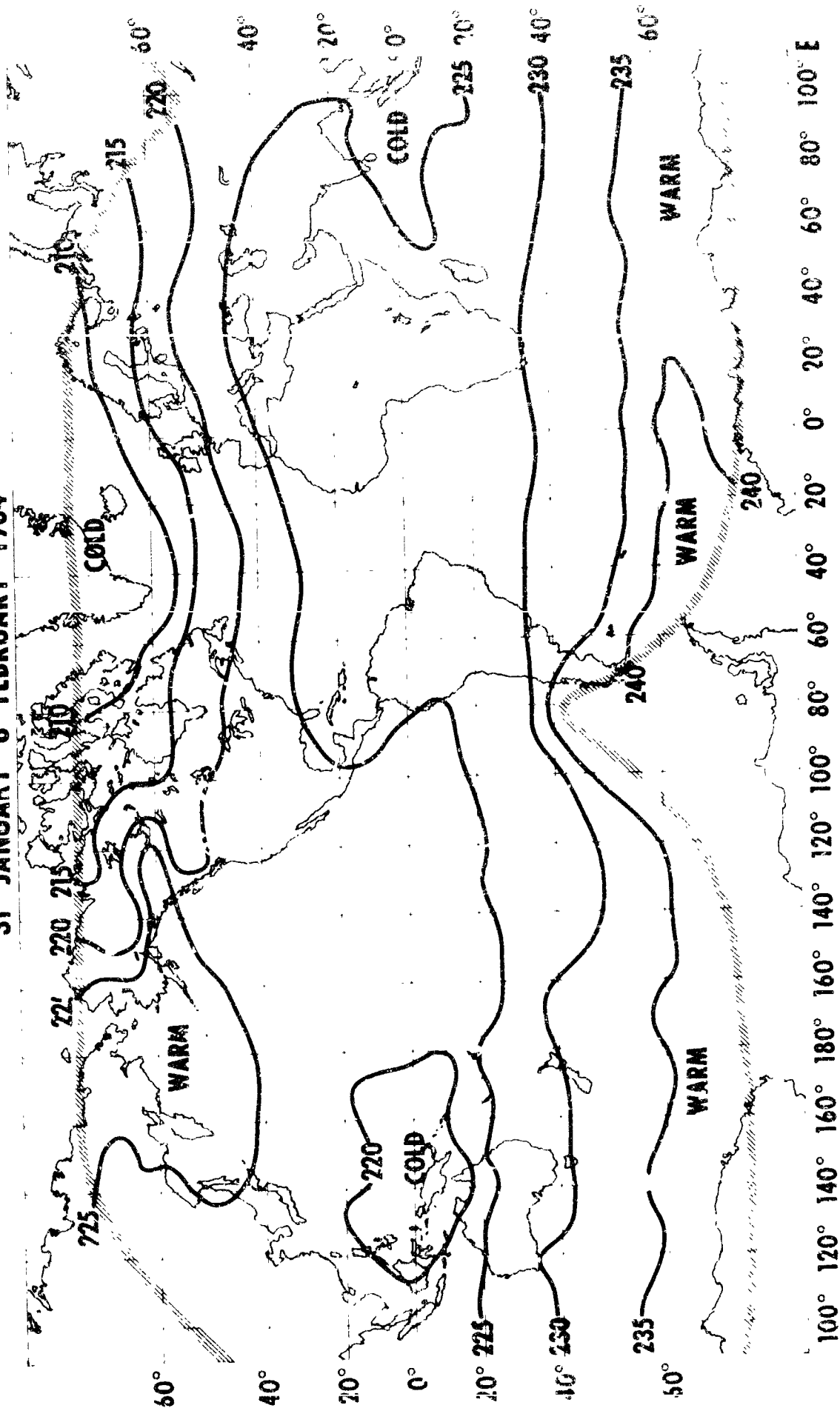


Figure 11b

TIROS VII, $15\ \mu$ T_{BB} [$^{\circ}K$]
 NADIR ANGLE 0-40°
 18-25 MARCH 1964

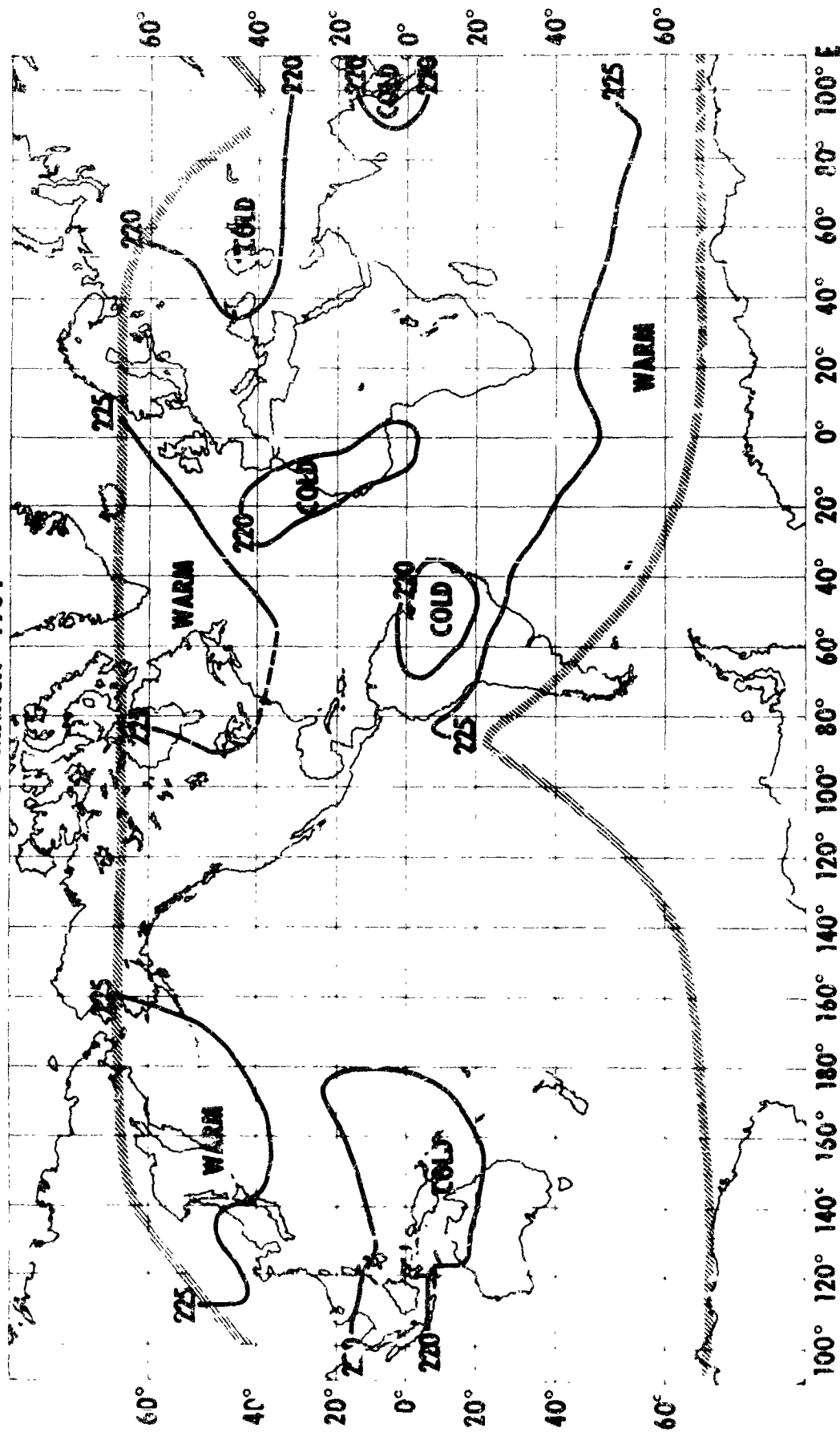


Figure 12